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A STUDY OF WIDE ANGLE OPTICAL SYSTEMS
FOR USE IN
VISUAL SIMULATIONS

NASA CONTRACT NAS 8 11775
MARSHALL SPACE FLIGHT CENTER

FINAL REPORT

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ABSTRACT

This study program was undertaken by the Goodyear Aerospace Corporation (GAC) for the National Aeronautics and Space Administration (NASA) to advance the current state of the art in the field of wide-angle optical systems used to generate visual displays for manned space flight simulation. Specific goals of the program were to survey the present state of the art and to provide specifications and design criteria for an optical system which will: (1) maximize depth of field viewed by the system; (2) maximize angular field of the system and hold it constant under all operating conditions; (3) minimize the working distance of the optical system entrance pupil from the viewed surface (model); and (4) be movable under computer control relative to a viewed surface in such a manner as to provide a continuous view which will be analogous to that seen from a vehicle undergoing six-degree-of-freedom maneuvers.

The information herein documented constitutes the final technical report provided for in the contract, covering the entire contract period 29 December 1964 to 29 June 1965. Previous to this a series of five monthly progress reports was submitted covering activity through the month of May 1965.

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ACKNOWLEDGMENT

The survey portion of this study owes much to those industrial and government organizations which provided pertinent information bearing on past and present activity in the field of wide angle optical pickups. The project team is particularly grateful for assistance rendered by the following organizations:

Scanoptic Incorporated, Woodside, New York

Photomechanisms Incorporated, Huntington Station, New York

F. B. MacLaren Incorporated, Huntington Station, New York

Farrand Optical Co., Inc., Bronx, New York

United States Naval Training Devices Center,
Port Washington, New York

Marquardt Corporation - Pomona Division, Pomona, California

Pacific Optical Corporation, Inglewood, California

Tinsley Laboratories Incorporated, Berkeley, California

GLOSSARY

The following terms and symbols, many of which are commonly used in various other areas of the aerospace industry, are specifically defined here for the sake of minimizing possible ambiguity and to introduce the reader to current visual simulation terminology as used herein.

nadir -	A point on the ground directly below (or coincident with) the instantaneous look point being simulated.
look point -	The point of vantage of an observer located in three-dimensional space whose visual field of view is to be simulated. Equivalent to the entrance pupil point, front nodal point or exterior center of perspective of an optical system.
center of perspective -	The point through which a perspective (sometimes called geometric) projection is taken.
entrance pupil plane -	The plane of the look point of an optical system, generally normal to the optical axis. Entrance pupil size determines the amount of incident light which the optical system will accept from any object point. The intersection of the optical system axis and the entrance pupil plane is the entrance pupil point.
field angle (α)-	The angular field of view (or energy acceptance) of an optical system, subtended at the entrance pupil point and determined by the relative sizes and locations of other elements of the optical system.

exit pupil plane - Corresponds to the entrance pupil plane except that it determines the amount and angular field of energy delivered by the optical system (to the image). The exit pupil point is at the intersection of the exit pupil plane and the optical axis.

optical system - An arrangement of transmissive and/or reflective elements used to transform, via electromagnetic energy, a two or three-dimensional array of information into image of that information. The resulting image may constitute either a planar or non-planar surface, depending on the optical system. The energy spectrum involved is generally thought of as being the visible spectrum, although this is not a firm criterion.

aperture (d) - The entrance pupil of an optical system. Its size (generally a diameter) determines the magnitude of the solid cone subtended at an object (information) point within which energy emanating from that point will be accepted by the optical system.

f/no. - The relative aperture of an optical system. Equal to the ratio of the system effective focal length to its entrance pupil diameter.

T/no. - The ratio of an optical system f/no. to the square root of its transmittance (t), the latter being a number equal to or less than unity.

vertical datum - An imaginary plane used as a reference in measuring the vertical locations of points on a three-dimensional terrain model. In practice the term may denote a surface (i.e., spherical) where relatively small scales are used.

course - The orthographic vertical or planimetric projection of the intended path of a vehicle within a three-dimensional system of coordinates.

track - The planimetric projection of the actual vehicle path.

heading (ψ) - The direction of the planimetric projection of the longitudinal vehicle axis with respect to an angular reference in the vertical datum or a plane parallel to it.

pitch (θ) - Angular motion of a vehicle about its center of gravity measured in a plane normal to its lateral axis.

roll (ϕ) - Angular motion about a vehicle center of gravity measured in a plane which is normal to its longitudinal axis.

yaw (β) - Angular motion about a vehicle center of gravity measured in a plane which is parallel to the lateral and longitudinal axes.

optical axis - Generally an imaginary straight line passing through the centers of curvature of all elements of an optical system. A practical system may have its optical axis folded (bent) at discrete points within the system.

translation -	Linear motion of a vehicle center of gravity along one or more of the three axes of a spatial coordinate system. One such axis is generally considered altitude while the other two define motion in a plane parallel to the datum plane.
culture -	Man-made structures or their depiction on a map, chart or three-dimensional terrain model.
contour -	A line joining points of equal elevation of terrain features. Usually presented as a planimetric projection of such lines.
contour level -	The distance above vertical datum of a contour.
elevation -	The distance above vertical datum to a given terrain point or point on a cultural feature.
altitude (h) -	The distance above some vertical datum to an airborne vehicle. Datum may be mean sea level or a single or average terrain elevation level.
model -	Replica at some scale of a physical entity. For visual simulation this entity is generally some type of terrain surface or a separate object or objects such as other vehicles.
topographic map -	A map which depicts, in two-dimensions, both planimetric and relief information.
planimetric -	The vertical projection of terrain and cultural information, as on a map or chart.
relief -	Terrain information describable in three dimensions.

distortion - Any variation from the classic definition of a distortionless image as one which is generated by a perspective projection, in which straight lines from object points are extended through the center of perspective to intersect an image plane which is normal to a central line of the angular projection field. Distortion is defined as a percentage of radial distance error in the image plane measured from its intersection with the central line. A key connotation of this definition, from the point of view of visual simulation, implies that imagery thus generated is (ultimately) viewed along an axis which is normal to the image plane at the central line intersection.

aberrations - Variations in the performance of an optical system as compared to the ideal or reference (perspective projection) performance implicit in a system of infinitesimal aperture.

look angle (δ) - Vertical angle at the look point between an object point and the local horizontal.

depression angle (γ) - Vertical angle subtended at the look point between the optical axis and the local horizontal. Equivalent to optical-pickup pitch angle.

optical pickup - Any of a group of devices utilizing an optical system to transform information contained on three-dimensional terrain (or other) models into one or more images which may be thereafter transferred to a display system providing a full scale (angular) reconstruction of the system field of view.

unprogrammed system - A visual simulation system which can simulate look points anywhere within the spatial volume from which the actual vehicle could be expected to view the particular set of object information stored by the simulator.

circle of confusion (c) Size of the smallest image detail which the optical pickup is required to provide.

depth of field - That portion of object space within which an optical pickup will provide image information at no smaller a scale than that specified by the circle of confusion size. Near depth of field (D_N) is the loci of the nearest limits of this object space. Far depth of field (D_F) is the loci of the furthest limits of this space. Both near and far limits may be considered as measured from the entrance pupil point radially outward.

effective focal length (F) - The focal length of an optical pickup considered as a whole. It results from the locations and focal lengths of individual optical elements of the system.

slant range (R_a)- Distance from the entrance pupil point directly to an object point.

ground range (R_g)- Planimetric projection of the distance from the nadir point to an object point.

magnification (m) -A measure of the ratio of image size to object size of an optical system.

object distance (s) Distance along the optical axis from the entrance pupil point to a selected point in the object space for which the system is focussed. If the object is a plane, its intersection with the optical axis is generally used. When the object is three-dimensional the selected point must reflect the desired depth of field.

image distance(s')-Distance along the optical axis from the exit pupil point to the intersection of the optical axis and image surface.

hyperfocal distance (H) - A calculated object distance governing the depth of field of an optical system. Depth of field is generally considered to extend from one half of the hyperfocal distance out to infinity. In visual simulation, where object distances can become very small, this relation no longer holds—the near depth of field can never be less than half the object distance for which the system is focussed, if the far depth of field is to remain infinite.

illumination (E)- The amount of light energy incident on a surface or point.

brightness (B)- The amount of light energy emanating from a surface or point.

working distance - The minimum distance (a slant range) between the system entrance pupil point and a point of object information. The latter point need not be within the optical pickup field of view. The dimension therefore has both optical and mechanical significance.

SECTION I - INTRODUCTION

1. GENERAL

In the last decade unprogrammed real time visual simulation has received increasing attention from all areas of the aerospace industry including government agencies, airframe and systems manufacturers and the airlines. This has come about by virtue of two primary factors: (1) the need for completely realistic, safe and relatively inexpensive crew training in complex vehicle systems; and (2) a burgeoning requirement for dynamic systems research simulators which are capable of completely closing the man-machine loop. This interest in turn has led to visual devices of varying sophistication to satisfy specific system requirements. A significant general advance was made recently with the introduction of reflective virtual image display systems which are inherently capable of providing wide angle scenes having high contrast and detail.

Unfortunately, image generation systems and data links used to provide inputs to such displays have heretofore been hampered by one or more limiting characteristics such as resolution, field of view, depth of field and the like. Certain techniques, while strong in one or two of these characteristics have been quite inadequate as regards the remainder. Experience has shown that certain of these characteristics must be optimized in a visual display if adequate overall simulation effectiveness is to be attained.

2. VISUAL SIMULATION IMAGE GENERATION METHODS

Truly realistic unprogrammed systems in general use may be categorized with respect to their basic information-extraction technique, which may fall into one of three categories:

(1) Optical pickups used with terrain (or other) model data storage

(2) Flying spot scanners used with planimetric data storage

(3) Point Source devices used with planimetric data storage

Of the three the first offers the greatest amount of optimization at the present time. The storage medium describes in great detail all three dimensions of object space; high quality displays may be realized through employment of high resolution television links; and the pickup can generally be made to simulate the angular and linear degrees of vehicle freedom required. Flying spot scanners are basically limited to two-dimensions of object space - object height information, if any, is separately generated. Resolution and simulation dynamic range are restricted. The point source technique has the same disadvantages in varying degree except that height information is simulable to a limited extent.

Recent examples of optical pickups used in landing simulators are highly sophisticated in that they are capable of accurately performing down to a few feet of real world object distance while providing fairly large fields of view and imagery of usable quality. However, terrain model scales employed are large in order to permit the relatively great working distances necessary to attain reasonable optical depths of field while still maintaining practicable illumination requirements. This model scale requirement has in turn greatly restricted the vehicle operating space available within any one model and also the maximum ground range visible from any simulated altitude.

Because of the many inherent virtues of optical-pickup visual systems this study program was sponsored by the NASA to investigate and improve performance in the above critical areas.

3. PROGRAM DESCRIPTION

A NASA-GAC Project Orientation Meeting was held at Marshall Space Flight Center, Huntsville, Alabama on 29 December 1964. This meeting, a prerequisite to the initiation of contractor effort, was held for the purpose of discussing the technical problems and further defining the aims and objects of the program. NASA personnel emphasized that effort was to concentrate on optical pickups per se, as defined elsewhere in this report. They explained that the subject study is a part of the program of the NASA Working Panel on Visual Simulation Technology and that its results will be of interest to personnel in all NASA Centers represented on the panel.

The study program was performed over a six-month period. Potential sources of information in government and industry were queried by form letter. A literature search for information relating to wide angle optical systems and pertinent subsidiary components and subsystems was performed. Basic types of optical systems design were studied to determine their advantages and disadvantages in regard to the intended application.

The major result of the program is the report herein documented, which cites results of the survey and presents detailed specifications for advanced optical pickup systems together with design information pertaining to recommended technical approaches.

4. CONCLUSIONS AND RECOMMENDATIONS

The most highly developed optical pickup devices are those with an approximate field of view of 60 degrees. This evaluation is offered on the basis of best overall system performance characteristics. Wider angle systems have been manufactured and are being used but the value of these systems is not considered as good in terms of overall systems performance.

The single-objective oblique optics system described herein is considered the best practical approach for immediately improving the performance of optical pickup systems with regard to angular field, depth of field and minimum working distance. These improvements will have negligible effect on the ability of the pickup to simulate the desired six degrees of maneuvering freedom (in terms of typical system motion requirements) for angular fields up to very near the limit of the wide angle field range (120 degrees). This system can be used with any standard television system link and thereafter displayed: either on a television monitor or, by projection, in a more sophisticated fashion such as the previously-mentioned wide angle virtual image system. It would have almost universal application to existing optical pickup-type simulators, thereby vastly improving their overall capabilities while in some cases reducing present complexity and cost of operation.

It is recommended that the present program be continued with emphasis in the following areas:

a. A firm design will be generated for a fully-articulated single-objective system having the characteristics described in this report (110-degree field, infinite depth of field and 50-60 mil minimum working distance). Empirical investigations will be conducted using a functional breadboard model of a system having a scale-down optical performance and manual control of the mechanical servo modes. A moderately-high resolution television system will be employed for a preliminary subjective evaluation of system performance quality. Incorporation of a color television system capability will be studied.

b. Fabrication and comprehensive evaluation of one or more prototype units to the above design will be done using existing visual simulation equipment having appropriately-scaled models (i.e., on the order of 1:10,000 or smaller) and a high resolution (1200 lines) television system.

c. Perform an analysis and firm design of a multiple-objective oblique optics system embodying a 150-degree or greater field of view, infinite depth of field, minimum working distance and a high resolution color television system.

d. Investigate ultra-wide angle single-objective type pickup devices employing both refractive and catadioptric systems. The major areas to be investigated are: motion simulation systems, and means of employing multiple pickup tubes for high system resolution. The highly-distorted images produced by these ultra-wide angle single-objective type pickups will also require study of display means. More particularly, it is recommended that these display means should reflect the use of virtual image display devices.

SECTION II - STATE OF THE ART SURVEY

1. GENERAL

The state of the art survey was started immediately after the initial coordination meeting at MSFC. Readily available in-house literature was reviewed, as was general knowledge of GAC visual simulation personnel. The program scope was outlined by defining specific areas of primary investigation (Appendix A) dealing with optical systems, closed circuit television and servo-mechanisms. Subsequent computer, in-house and patent search activity was concentrated in these areas.

The overall survey was quite successful in terms of volume. However the amount of truly new information obtained was insignificant. For this reason the number of individual literature items referenced in the appendices has been kept to a minimum to avoid redundancy. It is believed that the data herein documented is an accurate reflection of the current state of the art as regards wide angle optical pickups and associated television equipment for non-programmed visual simulation. Appendix D lists computer and in-house search references. Appendix E lists related patents.

2. SURVEY LETTER

A list was prepared of various organizations known to have developed, or be developing, wide angle optical systems for visual simulation. To this listing were added sources known to have experience and/or interest in real time visual simulation system in general plus sources which might be expected to have developments which could be used even though not expressly intended for such application. The last category covers manufacturers of electronic image conversion, amplification and display devices or components. A form letter (Appendix B) was prepared and copies mailed to those on the above list. A total of sixty-six organizations received copies of the survey letter. Responses to date amount to 22, or 33%. These responses include one in January, twelve in February, eight in March, and one in June.

The rate of responses was generally very low, so that some questions arose as to whether or not a total return could be expected within the period of the contract. Unfortunately, some of the more prominent organizations in the visual simulation field either did not respond at all, or indicated no interest or no available data. It should be noted that GAC, under another program, conducted a similar survey during the latter part of 1964, and that the resulting information is directly applicable to this study - particularly in the area of television systems.

3. LITERATURE SEARCH

a. Computer Controlled

The computer controlled library of the Defense Documentation Center (DDC), the Aerospace Research Applications Center (ARAC) and GAC were enlisted to conduct a comprehensive survey of available pertinent literature.

In all three instances descriptors were selected to encompass a significantly large number of possibilities related to visual simulation. GAC library personnel assisted team members in this effort. Returns were narrowed down to a minimum number, copies of which were then obtained for examination in detail.

A total of 187 references was obtained via the computer-controlled searches. The DDC and ARAC searches yielded abstracts while the GAC search resulted in titles only.

The most productive efforts were the ARAC and GAC searches. The DDC search, while providing a significant volume of references, failed to turn up much that is pertinent to the program. It should be kept in mind that much of the computer-source material is described only by title so that potential value is sometimes difficult to assess. In those cases where it was felt that a potential did exist however, the reference was ordered.

b. General In-house

This source included the Engineering Index, technical journals, and trade magazines, GAC's files and miscellaneous articles and papers located either in the engineering library or through references contained in other literature.

The bulk of search material was obtained via this effort. The survey team already had in its own files information on many visual simulators.

c. Patents

The patent search occurred in three stages. An initial review of the available patent material was made first, to define what specific areas were yet to be covered. A formal search was then conducted for applicable patents by known contributors. Finally, additional patents were sought when encountered in the literature.

4. TRAVEL TASK

Travel was reduced by about 50% from the original forecast. This was due primarily to a dearth of new systems or technology revealed by the survey. The following organizations were visited during the week of 21 June, 1965:

Scanoptic, Incorporated

Photomechanisms, Incorporated

F. B. MacLaren & Company, Incorporated

Farrand Optical Company, Incorporated

United States Naval Training Devices Center

Marquardt Corporation - Pomona Division

Pacific Optical Corporation

Tinsley Laboratories, Incorporated

The above eight organizations were visited in order to gain information in greater detail than had previously been obtained through correspondence, and to discuss with potential suppliers some critical aspects of the design criteria presented in Section IV of this report. Of the eight, all but the last two were visited in reference to existing and/or pending optical pickup systems contracts. The remaining two are leading suppliers of visual simulation system optical components. Appendix L describes data inputs of these contributors.

<u>Monday, 21 June</u>

Visited a team consisting of Scanoptic, Photomechanisms, and F. B. MacLaren. Scanoptic is a small concern whose main interest is optics. Photomechanisms and F. B. MacLaren design the electro-mechanical portions of their pickups. The Scanoptic pickup is one such effort developed about 1950, and since improved upon with the addition of two more models. The current maximum has a 98-degree field. A 106-degree field is considered possible with the same basic system. Quite a few of these systems have been manufactured for use in various simulators.

In response to questions on optical pickup servo performance capabilities, their personnel indicated that actual performance is better than their previously-submitted data sheets, and that they would forward these data to GAC. They also indicated that they believe the primary limiting factor to be the gear trains used in the drive linkages.

Tuesday, 22 June

(1) Visited Farrand Optical Company. This company has exploited the spherical-mirror concept for wide angle virtual image simulation displays and has since produced quite a number of these systems. Their response to the survey letter described general performance parameters of a wide angle, dual-channel optical pickup which they were not willing to detail. Through a misunderstanding GAC team members had expected to be able to see some of the equipment; this, however, was not the case. Their personnel indicated that the details of their pickup system are already in the possession of the NASA.

(2) Visited Naval Training Devices Center (NTDC). This visit was planned on a tentative basis only, since team members did not know how much of the day was to be spent at Farrand.

NTDC personnel said that their overall in-house effort is directed at coming up with a satisfactory display for visual simulation but that they were investigating the entire visual system spectrum to achieve this. They cited some 60-degree optical pickups that they obtained and are evaluating.

NTDC has obtained a wide angle system that utilizes a single wide angle lens together with three television cameras for pickup, and a similar f/1.0 projection configuration for a display on an aluminum-painted hemispherical screen. The system, used as a ship-docking simulator, operates with an HO scale model and provides a 153-by-60-degree field at 4 foot lamberts screen brightness. Simulated visual range is from 15 to 2000 feet. We were unable to view this device at this time.

Pertinent projects by other investigators were also discussed. These sources have been queried, but have not as yet responded.

<u>Wednesday, 23 June</u>

Visited the Electronic Products Division of Marquardt. This division publicly disclosed last year an ultra-wide angle generation and display system. This is called the VueMarq system.

Team members were shown the existing VueMarq system, which is strictly a photographic device. The display uses the resulting single-frame color transparency, and features servo controls to simulate changes in attitude about the stationary pickup system (camera) pupil point. For real time simulation of the type considered herein, the concept appears restricted; Marquardt has cited a conventional pickup in several of their simulation system proposals.

Marquardt is working on a contract from NASA Langley to develop a 4000-line television system for use with their VueMarq system. The television portion of the study is being handled by Automation Laboratories, a Marquardt subsidiary located in New York. The latter organization has also been queried, but without result.

Thursday, 24 June

Pacific Optical Company was visited. This company has a long history as a manufacturer of quality optics including several catalogued wide and ultra-wide angle objectives. They have built optics for visual simulation systems in the past. Team members were given a tour of their facility, which is fairly extensive and quite complete. Team members discussed at some length with their personnel the problems associated with optical objectives for pickup systems.

Their personnel cited a number of wide angle objectives in general use which were designed by Pacific. They also stated that they have a considerable number of wide angle designs available which can be modified with relative ease to meet specific visual system requirements.

Friday, 25 June

Visited Tinsley Laboratories. Tinsley specialize in large-aperture optics and catadioptric optical systems utilizing both spheric and aspheric elements which extend well up into the so-called massive range.

A major effort in recent years has been devoted to the manufacture of extremely large (up to 120 inches presently) optical elements - both refractive and reflective. These have been primarily for two applications: solar and visual simulator manufacturers. The visual simulation elements are used in virtual image displays. This company is unique in that it currently possesses a capability for providing virtually any form of massive-optics display such as the Farrand or the Marquardt wide angle systems.

Their personnel stated that 80 to 90 extra large mirrors have been produced to date, but with significant scrappage. The latter has been due primarily to a requirement for element truncation. When large optical elements of this size are truncated, internal stress imbalances become appreciable and breakage can occur in a totally unpredictable fashion.

Tinsley is currently undergoing a 100% facility expansion. One result of this is to be a physically-isolated collimation test cell of extreme size, with provisions for further growth. They are also working on a 140-inch grinding machine. Their parent company, Optical Coatings Incorporated, currently does most of their coating work. Their personnel stated that the vacuum facility at Space Technology Laboratories can be made available when required. This facility can handle elements up to 23 feet in diameter.

SECTION III - TECHNICAL INVESTIGATION

1. GENERAL

This section is intended to define the technical scope of the program through definitions and discussion of the specific parameters to be improved, and by consideration of the subsidiary (non-optical) functions and devices which are associated with an advanced optical pickup design.

The functional implications of angular field, depth of field, working distance and angular motion - all basic quantities which are desired to be improved upon - are considered independently in the following paragraphs. Angular field and depth of field result from a selection of other well known optical-system parameters such as focal length, circle of confusion and effective aperture. Each however, due to dependence upon common optical quantities, is also very much dependent upon the other, so that it is not possible to optimize on a separate basis. The third quantity is partially dependent in that a given objective lens design prescribes the location, relative to the first surface, of the entrance pupil point, which is the center of visual perspective or simulated-observer location.

Angular motion capability effectively depends on the location of the entrance pupil and the angular field. If the pupil is relatively far from the first optical surface and the angular field is not too great, then motion simulation can be achieved by path-bending components near the pupil location. If not, then it is generally necessary to move the entire optical pickup about the pupil point to simulate the required attitudes.

2. PROBLEM DEFINITION

a. Angular Field

(1) Rectilinear Propagation of Images

Optical systems which transmit the image of an object to a flat field in a rectilinear (undistorted) fashion are limited in angular coverage and usefulness. Equation (1) is the function that describes such systems.

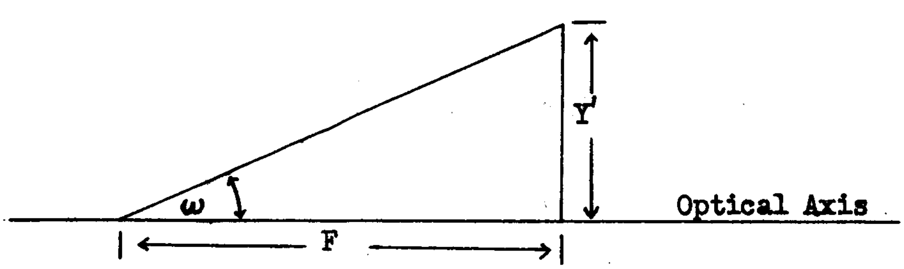
$$F = \frac{Y'}{\tan \omega} \tag{1}$$

where

F = focal length

Y' = image height (measured normal to and from the optical axis)

ω = object angular displacement



Most lenses are designed for rectilinear propagation of images but angular coverage requirements are generally small (i.e., less than 60 degrees). Wide angle lenses (from 60 to 120 degrees) have been designed which yield rectilinear performance up to 100 degrees with aperture ratios of approximately f/6. The Hypergon lens ranges into the realm of ultra-wide angle lenses (greater than 120 degrees) with an angular field of 135 degrees at f/32. Although wide angle and indeed ultra-wide angle fields can be obtained with distortion-free performance, the classes of symmetrical lenses used to obtain these characteristics are not considered advantageous for optical pickup devices. The recessed entrance pupil and illumination falloff in the image are the primary disadvantages.

As the field of view increases for a single objective lens the desired condition of having an external entrance pupil cannot be maintained. The advantages of an external pupil are discussed under paragraph d. (Six Degree of Freedom Motion Considerations). The external entrance pupil can be maintained for fields up to approximately 110 degrees. Such an objective lens however, would produce negative or barrel distortion. This can be corrected later in the optical pickup.

Maintaining luminous efficiency for a rectilinearly propagated image of wide angle would not be possible. The $\cos^4$ law would cause the illumination of an image point at a distance Y' above the optical axis to decline to an amount equal to the product of the axial image point illumination and the $\cos^4 \omega$. This would be 10.8 per cent of the axial image point illumination for a semi-field angle of 55 degrees. (See figure 1). The image brightness differential for progressively off-axis image points must be compensated for in rectilinearly propagated image systems of the wide angle variety. This is best accomplished with a continuously-variable transmission filter

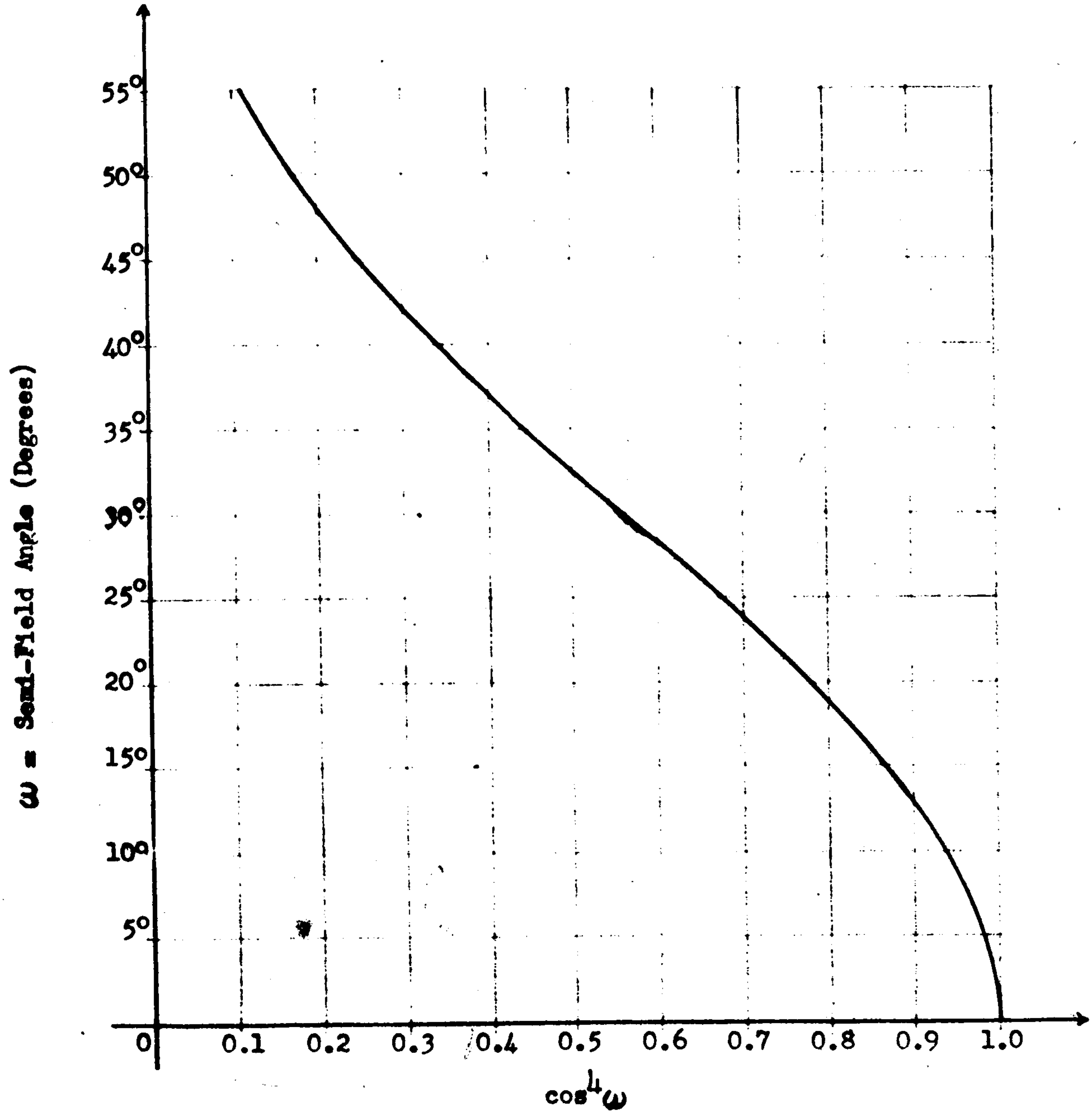


FIGURE 1 - COSINE FOURTH LAW vs. SEMI-FIELD ANGLE

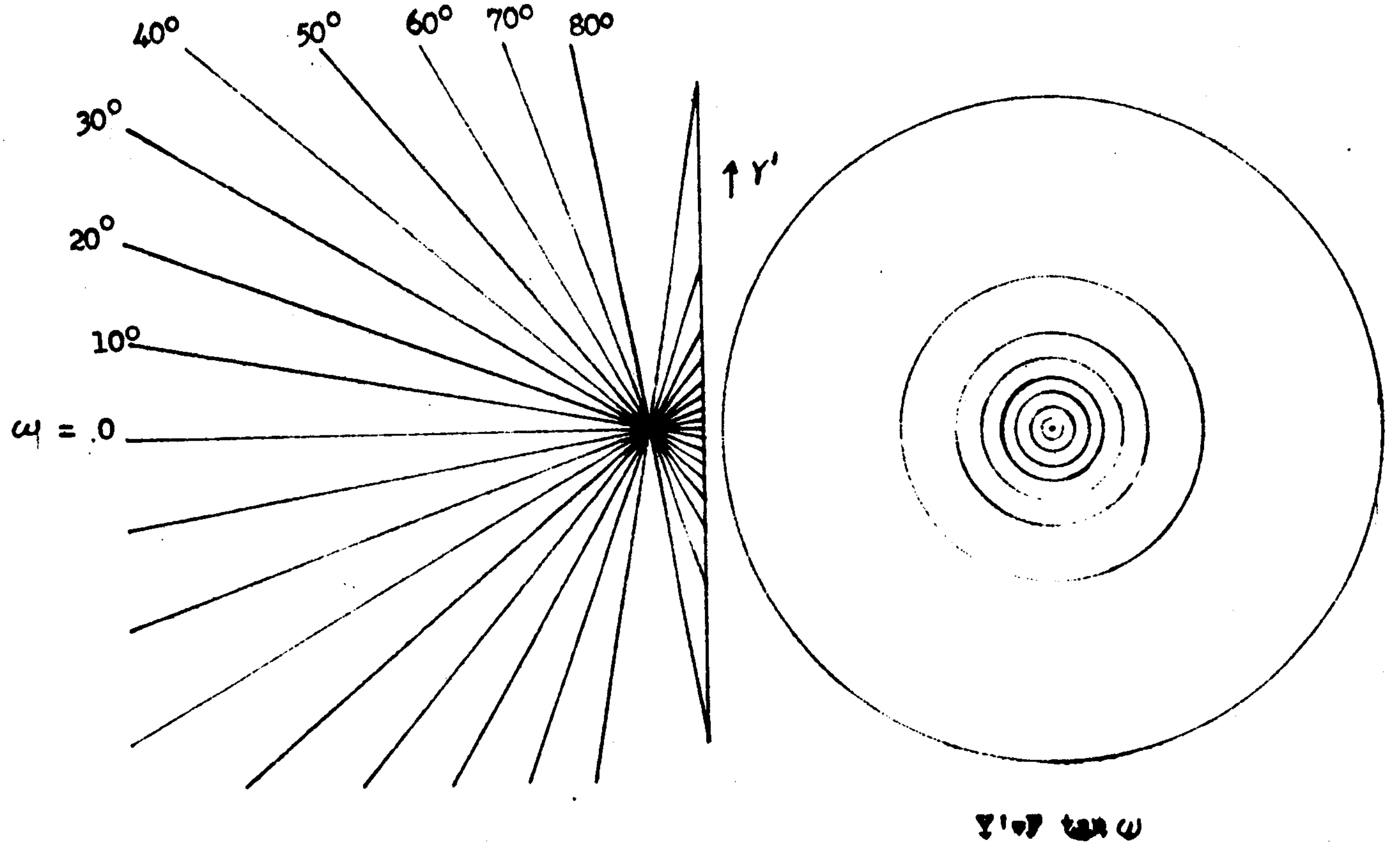
which attenuates the image to a level of uniformity compatible with television pickup tube characteristics.

Optical pickup devices for real time simulation systems are intimately associated with television systems. Some distortion can be corrected by altering the television scanning system in either the pickup or display. This subject is more fully discussed under television system parameters (Section IV).

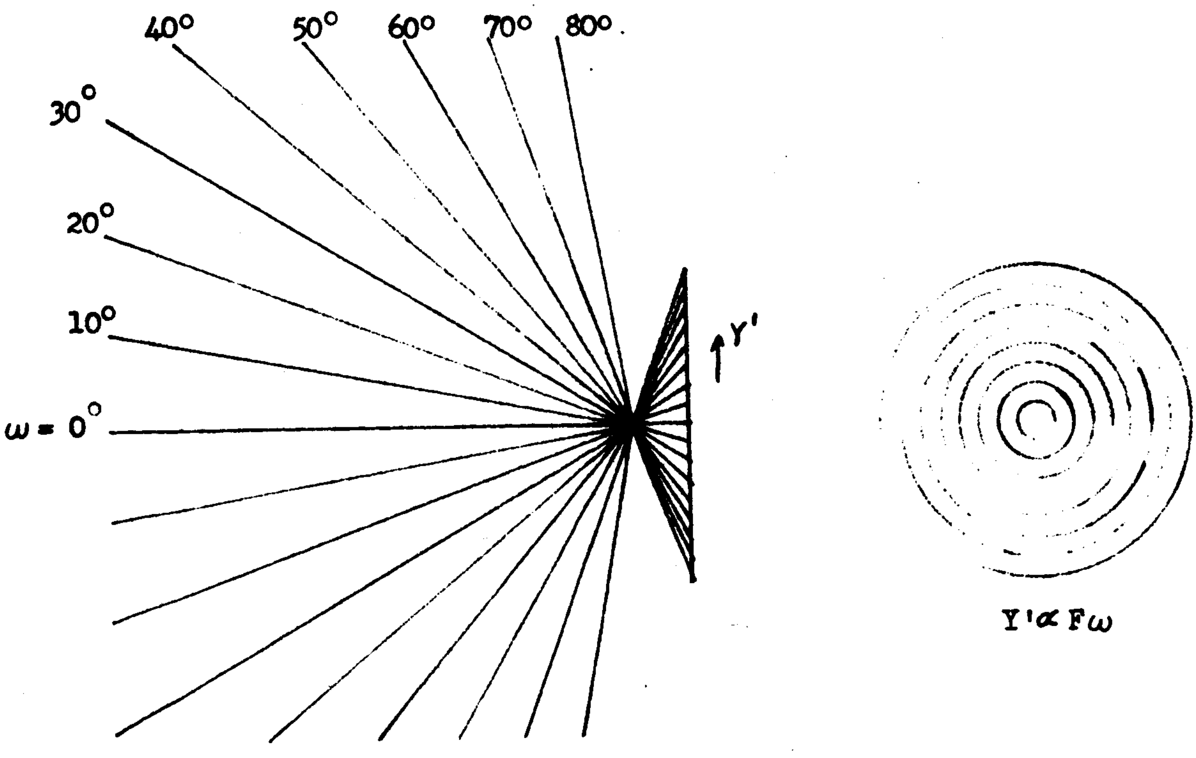
In general it is most desirable to have a rectilinearly-propagated image. Such systems do not require special means of display and resolution is fairly uniform in terms of bits of information per angular degree. As the simulated field of view gets more into the realm of ultra-wide angle views it becomes less desirable to employ rectilinearity-propagated images. This is true from the optical pickup design standpoint and that of the display device.

(2) Non-Rectilinear Propagation of Images

As simulated fields of view approach the upper limits of wide angle systems and continue into what are defined as ultra-wide angle fields it becomes necessary to examine non-rectilinear optical pickups. Figure 2 illustrates the characteristics of a special case of non-rectilinear propagation where angles in the object space are equated to distances off axis in the image space.



A. Rectilinear Propagation



B. Distorted Image Propagation

FIGURE 2 – TWO TYPES OF IMAGE PROPAGATION

The $\cos^4$ law is controlled within reasonable limits by restraining the image height Y'. More specifically, the image displacement angles are held small. The proportionality constant for zero distortion,

$$\frac{\tan \omega'}{\tan \omega} = \text{constant}$$

no longer holds. The ratio of the tangent of the image angle to the tangent of the object angle does not equal a constant. The type of distortion cited in the above system is barrel distortion, wherein magnification diminshes progressively as a function of object angular displacement.

Very many wide angle and most all ultra-wide angle lenses yield barrel distortion. A class of lenses specifically designed for such purposes are the reverse telephoto series. These lenses offer high resolution over wide angles with low f/nos resulting in a distorted image. Several simulation devices employ such lenses as their optical pickup system objective. These pickups were formerly used in programmed devices but several real time simulators now use this approach. The major drawbacks are restrictions on closeness of approach to the model due to a highly recessed entrance pupil, angular motion simulation problems, and real time, television link, problems in terms of resolution bits per angular degree.

An example of the resolution problem from the viewpoint of angular coverage can be explained in the following example:

Horizontal field of view = 110 degrees

Horizontal television resolution = 900 TV lines (on axis only)

The angular resolution of such a system equals (4:3 aspect ratio),

$$\frac{110\ (60)}{600} = \frac{\text{minutes of arc}}{\text{optical line pairs}}$$

= <u>11 arc minutes resolution</u>

The television system indicated is a state of the art high resolution system. It has a bandwidth of 32.5 mc. The best horizontal resolution for matched vertical and horizontal performance is 900 TV lines on axis. Resolution in the corners would probably drop to 700 TV lines. This would present what is considered as a marginally acceptable display. The peak resolution is 11 minutes of arc. Marginal acceptance for visual simulation is defined here as 12 minutes of arc resolution minimum in the area of greatest interest. Good resolution performance is defined as a minimum of six minutes of arc resolution. The actual figures for simulation performance are usually tailored to the specific simulation task or mission. Simulation devices need not duplicate human eye resolution of one arc minute except in rare cases.

Ultra-wide angle lenses may be considered rectilinear from a systems standpoint if the taking lens and projection display lenses are matched to be the equivalent of a symmetrical lens system. Regarding an ultra-wide angle lens from the standpoint of being the objective lens of an optical pickup however, presents formidable problems for an intermediate link such as television. An example was previously explained on the basis of using a high-resolution television system with an undistorted wide angle field of view. If we now consider the same case and present a barrel-distorted image on the television pickup tube, the equivalent perspective of the previous example would require electronic means of correction if the video output is to be a true perspective representation. The nature of barrel distortion is incompatible with television resolution characteristics. The decrease in angular magnification with object angular displacement-indicative of barrel distortion - further degrades the angular resolution system performance if corrections are attempted by non-linear raster scanning. Ultra-wide angle fields of view can be obtained by various optical systems to the extent of covering 360 degrees horizontally by 240 degrees in elevation. However, single television camera systems employing flat focal planes, which venture into the realm of ultra-wide angle performance, must inherently possess negative distortion. Several such systems exist, including the reverse-telephoto series of lenses as well as various catadioptric designs.

b. Depth of Field

(1) Geometry

Hyperfocal distance, H, is that object distance for which all information located between H/2 and infinity will be in focus on a single plane with a resolution defined by the chosen circle of a confusion. Figure 3A shows a bundle of rays from infinity focused at the primary focus of the lens and a bundle of rays emanating from the point H focused at a distance F + X in the image space. The ray bundle from H describes a circle of confusion, c, on a plane at F. As the desired value of c is arbitrarily decreased by adjustment of other optical parameters the information from H becomes more highly resolved on the plane at F. The following derivation defines H:

$$\frac{1}{F} = \frac{1}{s} + \frac{1}{s'} \qquad (1)$$

From Figure 3 A

$$\frac{1}{F} = \frac{1}{H} + \frac{1}{F+X}$$

$$X = \frac{F^2}{(H-F)} \qquad (2)$$

and

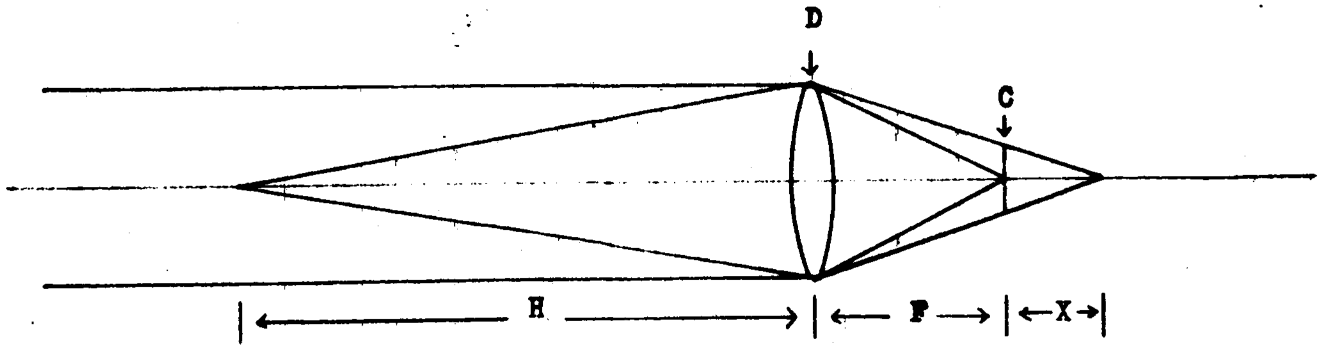
$$\frac{c}{2X} = \frac{D}{2(X+F)}$$

$$X = \frac{cF}{D - c} \qquad (3)$$

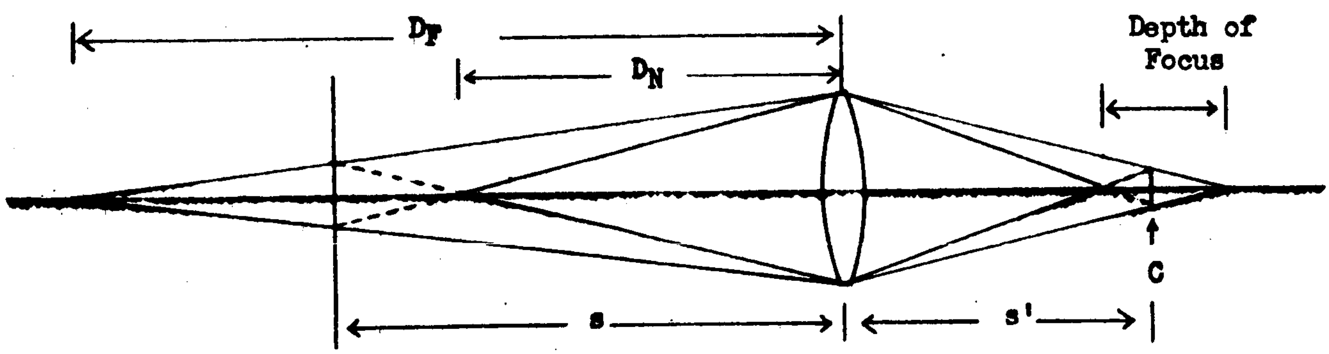
Equating (2) and (3)

$$\frac{F^2}{H - F} = \frac{cF}{D - c}$$

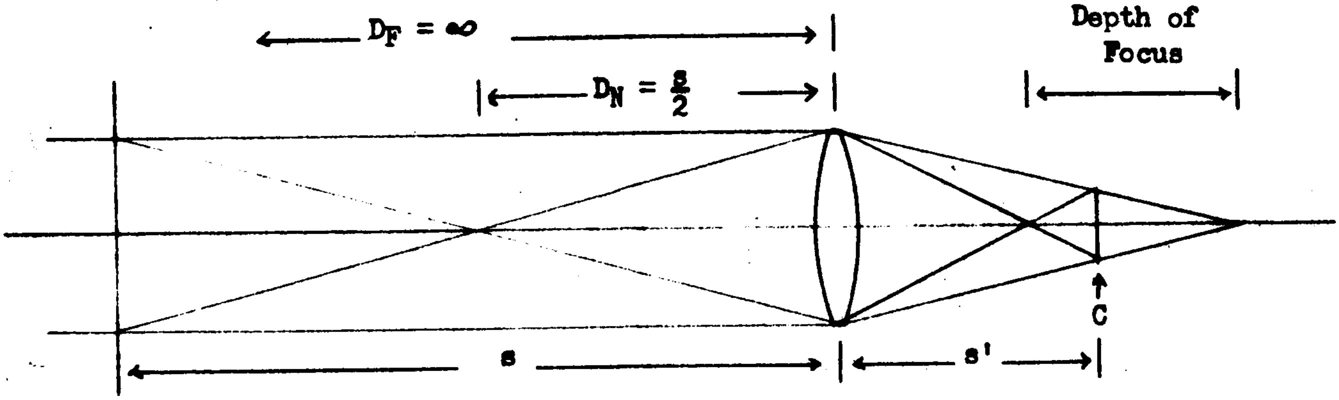
$$H = \frac{D}{c} F = \frac{F^2}{(f/no.)c} \qquad (4)$$



A. Hyperfocal Distance Math Model



B. Finite Far Depth of Field



C. Infinite Far Depth of Field

Figure 3 - HYPERFOCAL DISTANCE AND DEPTH OF FIELD

Equation (4) defines the hyperfocal distance H as a function of the focal length, relative aperture and the circle of confusion. When the circle of confusion is located on a plane at some image distance greater than F as in Figure 3B, there are two limiting ray bundles corresponding to two different image distances, the distance between which defines the depth of focus. There are also two object distances corresponding to the two image distances which define the near (D_N) and far (D_F) depths of field. All information lying between D_N and D_F of Figure 3B will be in acceptable focus (as defined by the selected value of c) on the plane at s'. The near depth of field and the far depth of field are defined by:

$$D_N = \frac{Hs}{H + (s-F)} \tag{5}$$

$$D_F = \frac{Hs}{H - (s-F)} \tag{6}$$

Figure 3C shows the geometry for an infinitely-far depth of field. This condition is attained when the lens is focused for an object distance equal to the hyperfocal distance.

Then, equations (5) and (6) reduce to $D_N = \frac{H}{2}$ and $D_F = \infty$.

c. Working Distance

Model working distance or the closeness of approach to a model is dependent on how close the center of perspective (entrance pupil) can be brought to the model surface. In an external-entrance-pupil-type system the controlling parameter becomes the radius of the entrance pupil. This neglects the path-folding media (prisms, mirrors).

Figure 4 is a curve relating angular resolution to entrance pupil diameter. This curve is based on theoretical diffraction - limited performance using monochromatic light where:

$$\alpha = \frac{1.22\,\lambda}{D}$$

$$\text{angular resolution} = \frac{\text{constant x wavelength of light}}{\text{entrance pupil diameter}}$$

Most existing optical pickups employ entrance pupils one to two millimeters in diameter. Under pure theoretical conditions these pickups cannot resolve better than one minute of arc. The best performance claimed by one manufacturer using a 1.6 mm pupil is approximately 3 minutes of arc resolution on axis only. This amounts to half the theoretical limit for the very best condition of performance. Progressive off-axis imaging must produce formidable losses in resolution. When working with three-dimensional models, sacrifices must be made for close model approaches. A practical limit on closeness of approach based on pupil considerations would be approximately 0.025 inches. With hardware implementation such as angular motion simulation devices the practical limit on approach would be more nearly 0.050 to 0.060 inches.

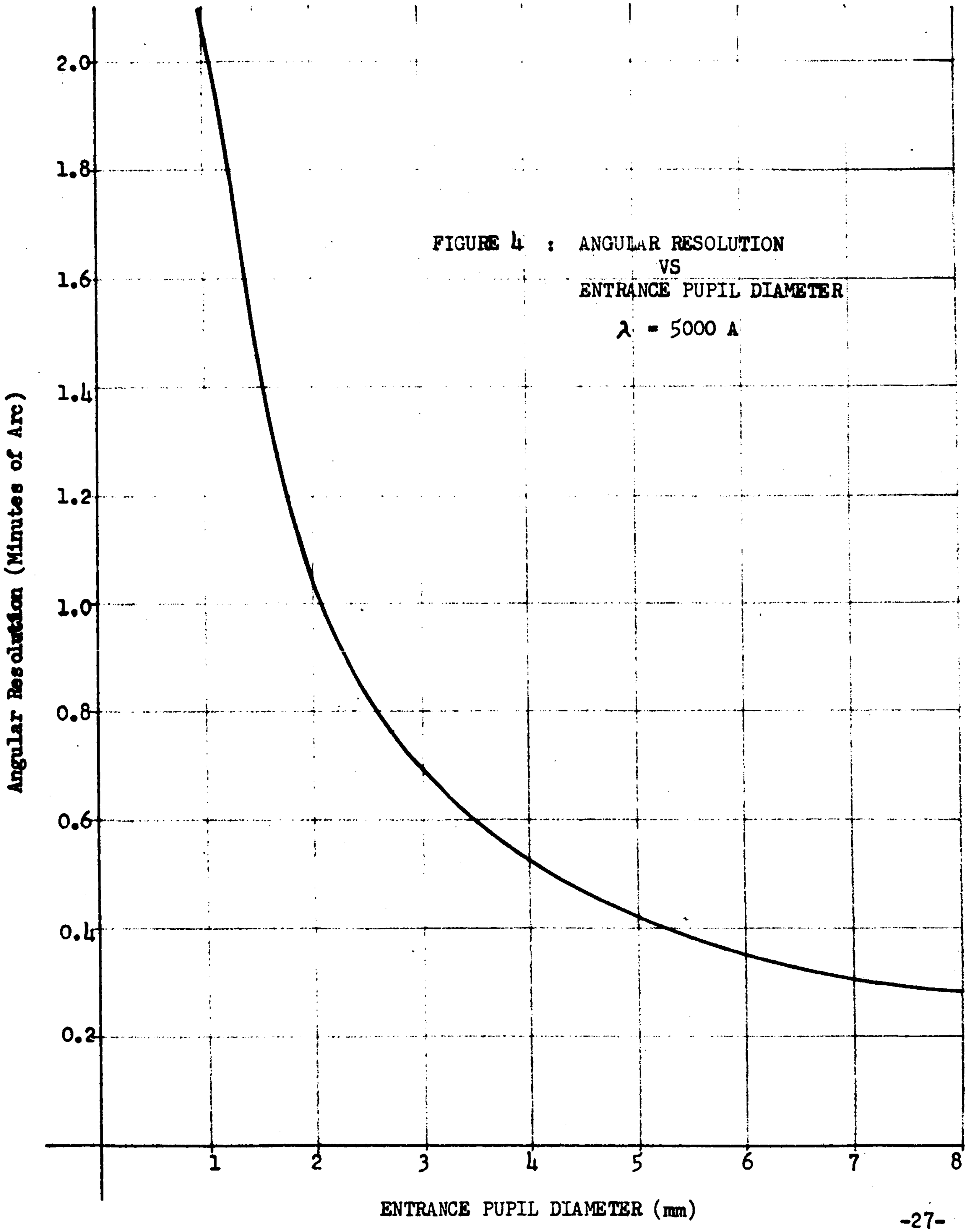


FIGURE 4 : ANGULAR RESOLUTION VS ENTRANCE PUPIL DIAMETER

λ = 5000 A

d. Motion Requirements

Translational motion freedoms are required in optical pickup simulation devices but need not receive special consideration insofar as the design of the optical pickup itself is concerned. The angular degrees of vehicle freedom (roll, pitch, and yaw) are more critical to the design problems of optical pickup devices and have therefore been studied extensively.

If ultra-wide angle probes are employed, which essentially view hemispherical data, motion simulation considerations must be examined differently from devices having more restricted fields.

The exact magnitudes of roll, pitch, and yaw motions to be simulated are dependent on a specific simulation system requirement. Some general remarks concerning the simulation of these motions is important.

Fly-around capability is most always desirous. This would indicate the need for at least a 360-degree optical pickup heading change capability. This motion has been provided in both limited and continuous fashions in existing designs. Roll in optical pickups is usually easy to provide as a continuous motion. Pitch motion can be simulated from horizon to horizon in some pickup devices. Although this magnitude of pitch simulation is most generally unnecessary under close-approach conditions, even greatly restricted pitch freedoms can, on the particular system, pose design problems.

e. Three-Dimensional Models

For space simulation two types of models are of primary interest: terrain and other vehicles. Both are important in terms of the objectives of this study program; however, terrain models are perhaps the most commonly thought of and are certainly bounded by the same if not greater problems and limitations insofar as model-making technology is concerned.

Terrain models have random surface upon which information of varying detail is found. This detail may consist of cultivated fields, single and grouped trees, hedges, roads, buildings, vehicles, complexes such as airfields or tank farms, dockyards and population centers of varying size.

A logical extension to the achievement of an optical pickup that permits very close working distances while maintaining or improving other basic parameters is to go to a smaller model scale. This has obvious advantages such as storage of a given terrain area in a much smaller physical simulator space, which in turn leads to a smaller translational motion system. In the general sense one might surmise that the cost of model and motion system also decreases, and this is true to a limited extent.

In the case of the translational motion system, decreased travel lengths permit a much more rigid structure per dollar of cost and therefore a more reliably constant motion datum with respect to a fixed model. As scale continues to decrease however, small-motion increments also become very small so that motion system servo resolution and accuracy must ultimately suffer.

In the case of the models themselves a great deal of hand labor is even now required to produce a model embodying the previously-described information at scales presently used (on the order of 1:3000). The areas where hand labor is required include: (1) cartographic compilation work; (2) depiction of desired information detail, including shape and surface treatment (i.e., texture and reflectance); (3) accurate mosaicking of individual model sections where a large total installed model area is required; and (4) verification of installed model depiction including vertical and planimetric data.

The most critical of these is the depiction of model detail. At a scale of 1:3000 a 100-foot long building wall is 400 mils (0.4 inch) long on the model. A 33-foot wall height however is only 133 mils. Experience has shown that the best way to model culture at extreme scales is by precision pantagraph routing equipment working in epoxy. The tool is a cutter rotating about the model vertical. The tool diameter is the limiting factor in achieving detail such as a building inside corner, and at the stated scale can be made small enough to attain quite realistic results. As scale decreases further, results become marginal.

The current state of the art is such that routed surface detail down to about seven (7) mils can be achieved. Inside corners, on close examination, reveal a definite radius but, for the type of terrain simulation usually desired this presents no problem since the requirement for close viewing from a stationary vehicle does not arise. Rather, close viewing of culture occurs only for low altitude overflight, wherein vehicle speed is such that the cultural object passes through the field of view at an increasingly greater rate as slant range decreases. Under these conditions when range has shortened to the point where this type detail is normally discernable, image motion has increased so much that considerable effort on the part of the observer would be required to distinguish much departure from correct structural feature geometry.

Detail of a discrete type, such as windows and doors can best be handled by use of discrete reflectance changes. A fence or hedge is depicted by combinations of detail routing and reflectance changes. Detail of very low relief, such as a plowed field can be simulated by a combination of surface texture and reflectance variation; pure artistic effects come into primary usage here.

Of course if cost is no object extremely, fine three-dimensional (geometric) detail can be effected quite satisfactorily by painstaking hand carving. Similarly, textural detail could probably be reduced by use of photo-engraving techniques but this would require a working material other than epoxy and probably introduce temperature coefficient problems. Reflectance treatment detail can be done at scales limited only by the fineness of the tool used and perhaps minimum attainable reflectance material dimension— results should be compatible with achievable geometric detail.

To sum up, model scale reductions on the order of four to one, as referenced to the previously-cited figure, are readily attainable by use of current model-making procedures. This factor can probably be improved by an additional factor of 1.25 to 1.5 if model cost is not a significant criterion.

3. OPTICAL SYSTEMS

a. Dioptric

Wide angle views may be accomplished by several means. For a refractive system a straightforward approach might indicate using a single objective lens. As the field of view increases the depth of field increases for a given format (all other parameters being equal). This characteristic is illustrated in Figure 5 . It is deceptive to view these characteristics without recognizing some important factors which lead to systems problems as discussed in Section III.2.a.

In most optical pickup devices employed in visual simulation it is desireous to utilize the external entrance pupil approach. In such systems the entrance pupil (center of perspective) is an aerial image of the limiting aperture and precedes the objective lens. With the center of perspective in front of the objective element(s), system motions and closeness of approach to the model are easily attained. However, as the field of view increases, the entrance pupil recedes toward the objective lens. An extreme of this condition would be a wide angle objective lens of the reverse telephoto design. In this case the entrance pupil is physically located inside the lens itself.

It is an objective of this study to establish a reasonable limit on the field of view attainable with the external exit pupil approach. For a single objective lens this approach seems limited to wide angle pickups ($<$120 degree field of view). A single objective lens system with a 110 degree field of view is considered feasible.

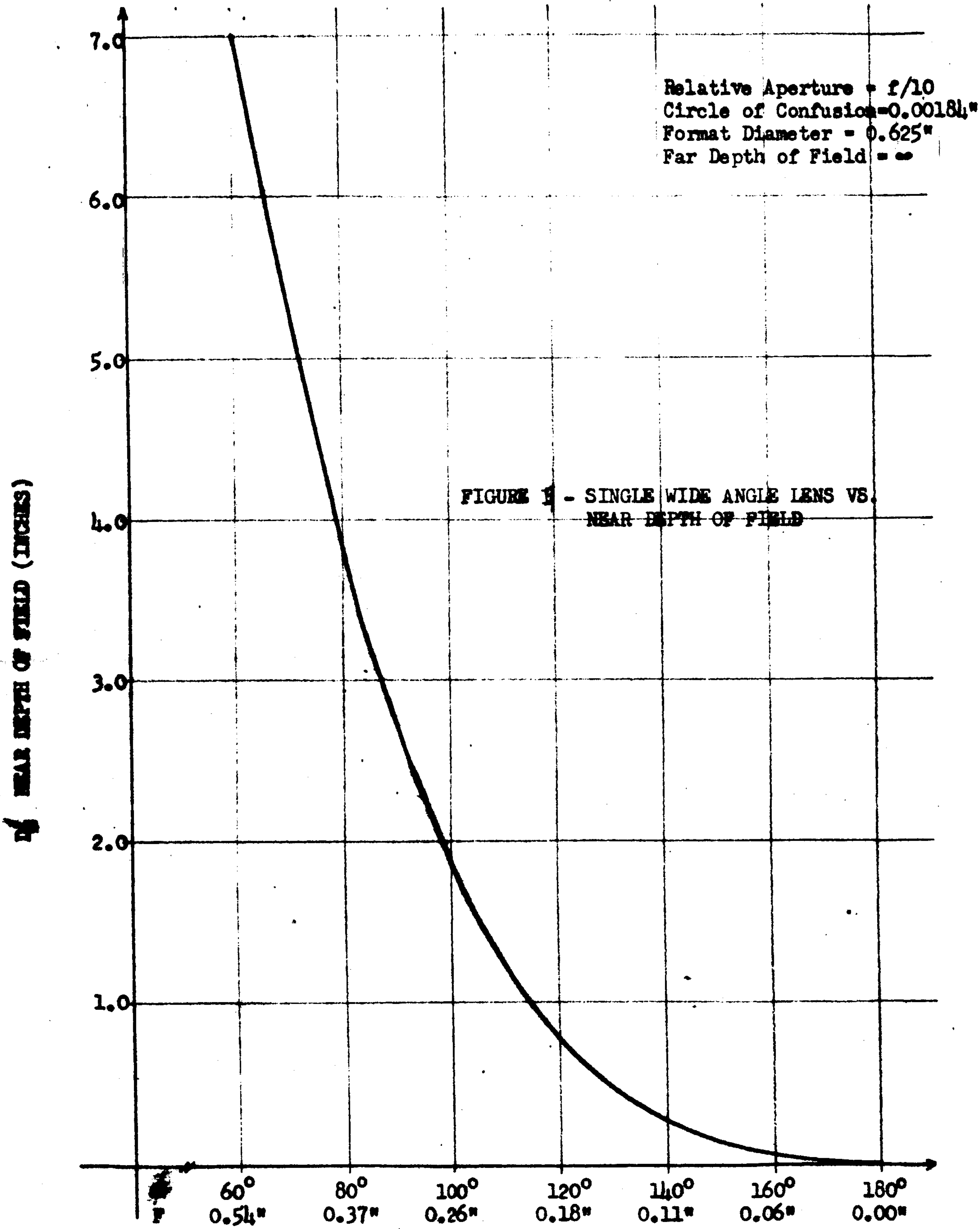


FIGURE - SINGLE WIDE ANGLE LENS VS. NEAR DEPTH OF FIELD

= ANGULAR FIELD OF VIEW

F = EFFECTIVE FOCAL LENGTH

Three types of objective lenses have been investigated. They are designs similar to Erfle eyepieces (see Figure 6A), Wild eyepieces (see Figure 6B) and high power microscope objectives (see Figure 7). These are presently considered the most promising type designs to pursue for use with the external entrance pupil approach.

Although distortion will probably not be fully corrected optically for the 110 degree single objective system, the magnitude will be relatively small. Subsequent correction can perhaps be best accomplished in the television system.

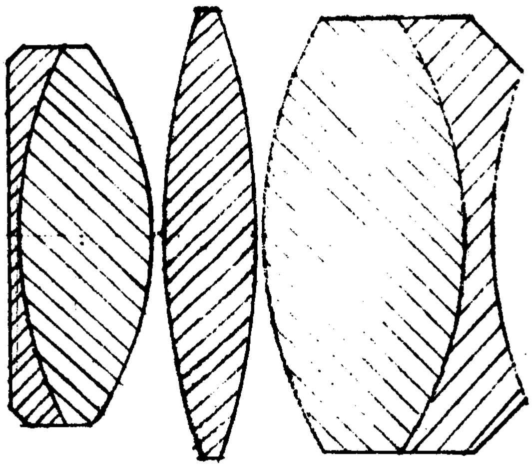
Untra-wide angle lenses ($>$ 120 degrees) are available in a large selection of designs. Most of these designs were developed for aerial reconnaissance purposes. Characteristics of some of these lenses are as follows:

Hypergon - f/16, 135 degrees

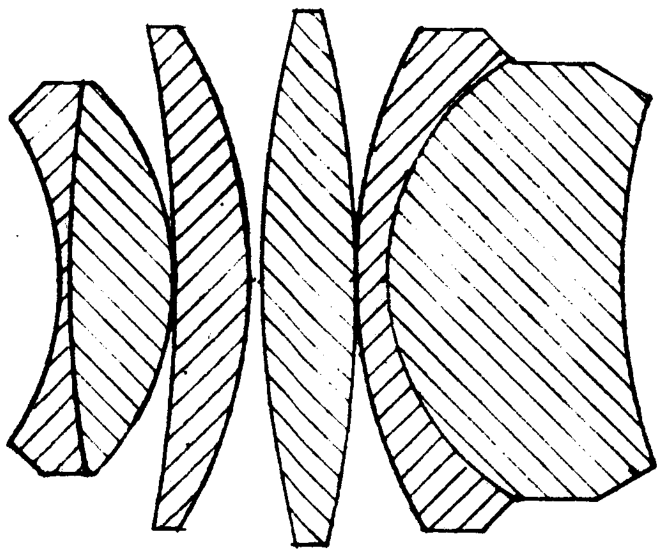
Pleon - f/8, 136 degrees.

Although these lenses do not exhibit extreme distortion problems it is doubtful that they will suit the purposes of a wide angle pickup as well as other lenses with extreme distortion which are now available.
These are the reverse telephoto series of lenses. Fields of view covered by these lenses range up to hyperhemispheres with 270 degree field angles. These lenses become highly attractive because of their low f/nos. and high resolution.

Implementing any of the ultra-wide angle lenses in an optical pickup device poses formidable problems in real time simulation of vehicle dynamics. Some ultra-wide angle concepts have been considered but in



A. ERFLE EYEPIECE



B. WILD EYEPIECE

FIGURE 6 - OBJECTIVE LENS TYPES

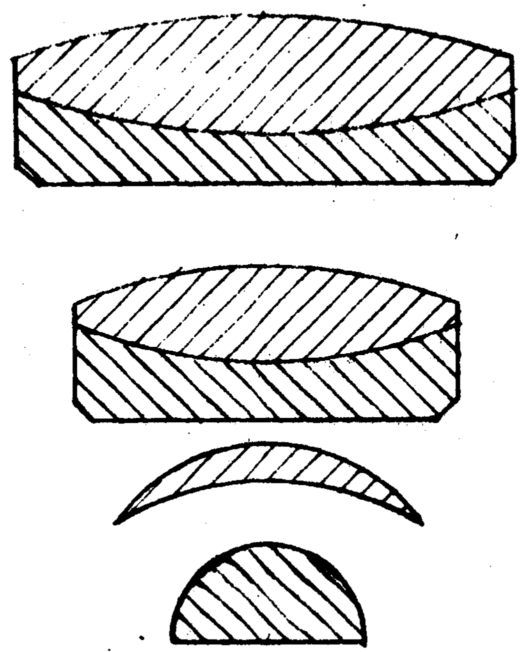


FIGURE 7 - HIGH POWER MICROSCOPE OBJECTIVE

these systems it is felt that the display means must be intimately associated with the pickup device. This is particularly true because of the distortion parameter. The overall design of optical components between the objective lens and the pickup tube is facilitated with the highly distorted image of the reverse telephoto. The display system however, must in this event compensate for this condition.

Inasmuch as these wide angle systems will be used in conjunction with closed circuit television systems employing a photocathode, it is necessary to consider the interaction of the optical and electronic systems. When an undistorted image is produced on the photocathode, field of view of the optical pickup is related to its focal length and the useful diameter of the photocathode.

Fig. 8 is a plot of the diagonal field of view vs. effective focal length for particular values of the useful diameter of existing photocathodes.

b. Catoptric

Pure reflective systems for use as pickup devices have not been deeply investigated. Catoptric systems alone do not offer the design freedoms inherent with refractive or catadioptric techniques.

c. Catadioptric

Particular consideration has been directed to catadioptric systems for ultra-wide angle pickups. Their use as wide angle pickups, however, includes significant disadvantages in terms of design, fabrication, and the implementation of a six-degree-of-freedom motion system. It is felt that refractive systems can best meet these wide-angle pickup requirements.

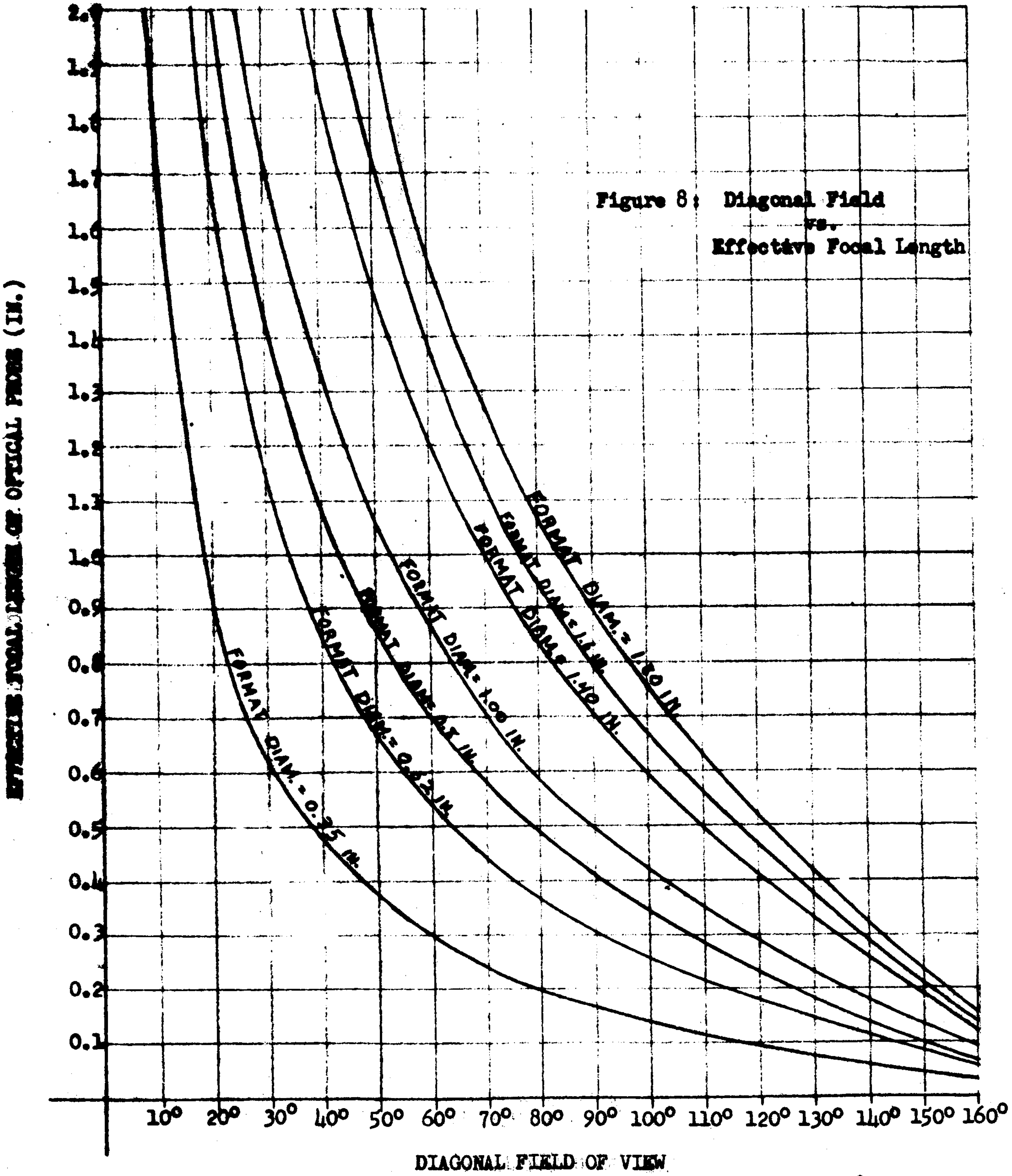


Figure 8: Diagonal Field vs. Effective Focal Length

Some ultra-wide angle pickups of catadioptric design offer certain advantages over pure refractive systems. The basic principle of these systems employes a convex mirror as the closest element to the model.

The basic geometry of one such system is shown in Fig. 9 . The system utilizes the basic principle that when a convex hyperboloidal mirror of eccentricity e is positioned to share a common focus and a common axis with an ellipsoidal mirror of eccentricity $\frac{1}{e}$, an angularly undistorted image is produced at the focal surface of the ellipsoidal mirror. The principle necessarily links the pickup (hyperboloidal mirror) with the display (ellipsoidal mirror). The size of the fields of view depends upon how much of the conic sections are used. If the majority of the conic sections are used, the fields approach 360 degrees about the common optical axis and more than 240 degrees in a transverse plane. The implimentation of the basic principle to achieve a real time optical pickup and display uses refractive elements to focus the imagery onto a photocathode.

Another catadioptric system employs a convex spherical mirror as the element of closest approach to the model. Again refractive elements are employed to form the final image on the pickup tube.

Such catadioptric systems, while offering ultra-wide fields of view, impose formidable design problems. The image plane formed by the convex mirror is highly curved and requires complex optics to focus the curved field on a flat-face photocathode. Also, the entrance pupil of such systems is recessed, causing severe design problems for vehicle attitude simulation.

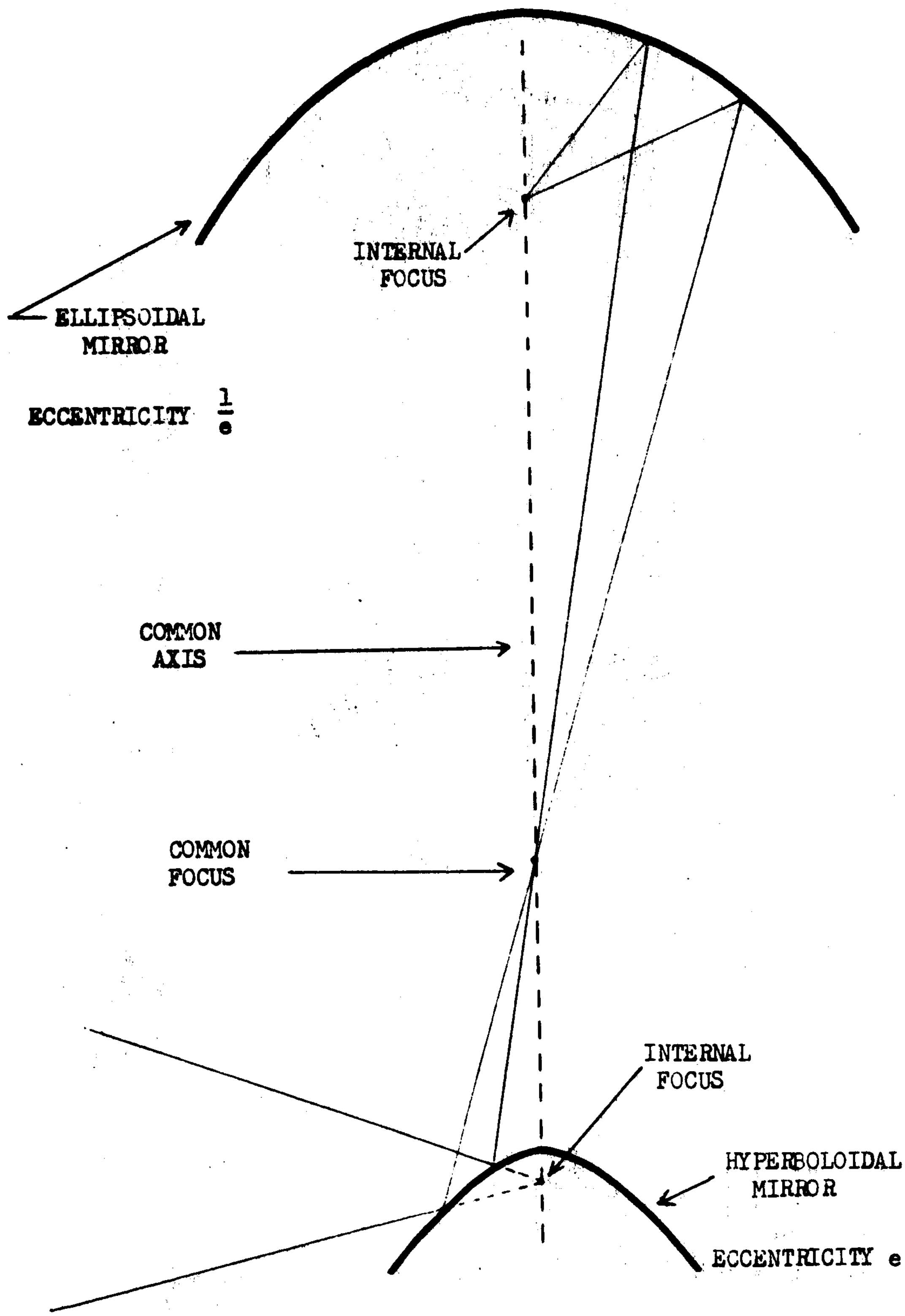


FIGURE 9 - HYPERBOLOIDAL-ELLIPSOIDAL MIRROR PRINCIPLE

Also, under the category of catadioptric systems can be included those devices which use plane mirrors for synchronously scanning model terrain. In addition to the optical problems of pickup design, formidable problems in mechanical design and electronics arise. Solutions to these problems are within the present state-of-the-art. At the present time, however, it is believed that the state-of-the-art for optical pickups can best be advanced by means of more conventional refractive approaches.

4. ELECTROMECHANICAL SYSTEMS

a. General

The optical pickup head will require servo-controlled motion of certain mechanical elements to achieve pitch, roll, yaw, focus and others as required.

The servo systems considered here are analog. A comparison of advantages and disadvantages of an a-c servo loop versus a dc servo loop indicate that it would be desirable to use an a-c servo with dc compensation networks. The accuracy requirements dictate that a type II servo system be used. With this type system a positional error between input and output occurs only during acceleration. A two-speed synchro system will provide position feedback. This feedback arrangement reduces the synchro electrical error effects by a factor of the gear ratio between the coarse and fine synchros.

The servo loop is made up of the following components:

1. Fine and coarse synchro transmitters.
2. Fine and coarse synchro control transformers.
3. Data switch
4. Demodulator
5. Integrator amplifier.
6. Compensation network.
7. Modulator
8. A.C. servoamplifier.
9. A.C. servomotor
10. Appropriate gearing.

The following is a general discussion of servo system performance in certain important areas and the effects of various subsystem components on that performance. Also included is a discussion of various types of servo motors.

b. Operation at Low Angular Rates.

The performance of a servo system at low angular rates depends on the system sensitivity. Sensitivity is determined by the maximum error voltage which may appear at the output of the error detector without any corrective action occurring. The maximum error multiplied by two will represent the system "dead space". This dead space creates a non-linear region of operation and causes erratic or jerky motion during starting and reversals. The lower the angular rate the more pronounced is the effect of dead space.

In the servo systems of interest the A C servomotor will contribute to dead space. Servomotor sensistivity is measured by the voltage on the control winding that is just sufficient to start the motor. Sensistivity is limited primarily by cogging. With the main field fully excited, the rotor tends to lock due to magnetic forces. The number of distinct locking positions matches the number of slots in the rotor. The motor cannot start unless the control field voltage generates enough torque to overcome cogging. The starting voltage required to overcome cogging plus friction is generally less the 3.5% of the rated control field voltage. Some small military motors are rated 1.5% of the rated control field voltage. This is not due to any improvement in design but just careful manufacture and special screening. Cogging effect can be minimized especially in smaller motors by appropriate design. According to vendor information this figure can be reduced to as low as 1%. Drag cup design motors have extremely high sensitivity, since the rotating member has no iron. Typical starting voltages are on the order of 0.5% of rated control voltage - about six times the standard sensitivity. However, stall torque per watt is about one half the value for conventional motors. As a compromise between the high performance of the squirrel-cage motor and the uniformity of the drag-cup unit, some small servo-motors use rotors of pure unlaminated iron. Although the over-all torque per watt input may be 20 per cent less for the solid rotor than for the squirrel cage, these units may be used to obtain extremely smooth performance..

The integrator amplifier in the loop will affect smooth operation at low angular rates. This amplifier will integrate the error signal during the dead space interval. Since there is no feedback signal during this time the integrator will continue to charge and result in an overshoot in the desired position.

The combination of the dead space and the integrator amplifier will result in erratic or jerky motion during slow starts and reversals. How pronounced this effect will be depends on the servomotor sensistivity, loop gain, friction, scale factor, and time constant of the integrator amplifier.

Use of a D. C. servo-motor in lieu of the A.C. servomotor would improve this condition some because the D. C. servomotor has a larger speed range. In fact, a comparison of other characteristics of a D. C. motor with those of an equivalent A. C. servomotor indicates that the D. C. motor would give the best overall performance.

The generation of radio frequency interference noise by the commutator and brushes, larger physical size and possible inaccessibility for brush replacement are disadvantages of a D. C. servomotor.

c. Noise

Noise can be defined as any undesireable signal. The noise level that can be tolerated depends on the system requirements. For high gain systems, noise is more of a problem and has to be kept at a minimum. Noise can enter a system by radiation or conduction. It can originate within system components or associated equipment. Radiation noise is attenuated by shielding. Conductive noise is attenuated by filtering.

In the subject servo systems component noise is considered to be of more concern than radiated and conductive noise. Noise levels at the synchro, demodulator and D. C. amplifier are discussed.

(1) Synchro Noise

Synchro null voltage may be defined as the residue voltage appearing across the secondary of a synchro when the rotor position is such that the in-phase fundamental voltage appearing across these terminals is zero. It consists of two basic components: quadrature fundamental null and harmonic voltages.

Fundamental null is a residue voltage having the same frequency as the excitation. This voltage is always in time phase quadrature with the output voltage at maximum coupling.

Higher time phase harmonic voltages are the other components of null. They are predominantly third harmonic and usually combine with the fundamental to yield total average null. Typical size 8 synchros have a fundamental mull of 34MV and a total null voltage of 53MV.

(2) Demodulator Noise

A demodulator will give a D. C. output only for input signals that are either in exact phase or 180° degrees out of phase with the reference voltage. Signal components in quadrature with the reference are not demodulated. This does not mean that they are entirely suppressed; rather, the demodulator does not produce any d - c as a result of this a c input, but it does produce an 800 cycle ripple which is 1% or less of the peak to peak output voltage. Since the demodulator output is D. C. and the frequency of the ripple would be 800 cycles, this ripple plus any higher frequencies that may be coupled from the synchro can be filtered with little effect on the dynamics of the system.

(3) Amplifier Noise

D. C. operational amplifiers would be solid state, chopper-stabilized amplifiers with low noise and drift characteristics.

Noise in D. C. operational amplifiers is made up of shot noise, partition noise, flicker noise, 1/f noise and thermal noise inherent in the active and passive components. The magnitude of this noise, referred to the input, can vary from 10 to 15 micro volts.

(4) Modulator Noise

Noise in a modulator consists of quadrature and harmonics at the output. In high-gain servo-systems performance is limited by saturation of the servoamplifier caused by quadrature components of the amplifier input signal. In addition, quadrature signals produce undesirable motor heating.

To reduce the quadrature content of this signal special rejection circuits are sometimes used. These circuits suppress the quadrature component while producing an output proportional to that component of the input which is in phase with the reference potential used. Percentage of quadrature in the output is typically 20 to 100 times lower than that in the input signal.

d. <u>Gear Trains</u>

In the servo system considered, gear trains will be required for the synchro transmitter, synchro control transformer and also between the motor and the load.

Any backlash in the synchro gear trains will contribute to the system error. Therefore, these gear trains must be of special design incorporating anti backlash features and precision parts. Gear trains have been fabricated with a maximum backlash of 0.5 minutes of arc.

Backlash in the gear train between the motor and the load has no direct effect on the accuracy but it does increase the chances of system instability if it is excessive. Standard motor gearhead designs are available in which backlash is normally under 30 minutes of arc, although 20 or even 10 minutes are available on special order. Also available are precision gearhead designs incorporating spring-loaded gears which reduce backlash to considerably less than 10 minutes of arc. Slip clutches can be employed to limit impact forces during servo transients.

The possibility of eliminating the motor gear train by using a direct-drive type of servo-motor was not encouraging. Available information indicated that the motor sizes were physically much too large for an optical pickup application.

e. Drift

Drift is an offset in the output of a balanced circuit for a zero input signal. Even though balanced units initially may not have any offset, such errors can develop in time. Any offset will contribute to the system error.

D.C. amplifiers, modulators and demodulators are susceptible to drift. The chopper stabilizing feature in D.C. amplifiers keeps the drift at a low level. The integrator amplifier in the forward loop which is schematically located before the D.C. amplifier and modulator will minimize any offset that may be present in these two components.

Drift in the demodulator can be minimized by a final nulling of the synchros. The contribution of drift to the system error is expected to be small.

f. <u>Servo Motors</u>

(1) Direct Drive Servomotors

Recently, the direct-drive d-c servomotor has assumed increasingly greater importance in the design of high-performance servos required by modern military and industrial systems. These servomotors find their principal application in gimbal systems for inertial platforms, camera mounts, radar antennas and the like, where the torquemotors' high torque-to-weight and high torque-to-inertia ratios, and lack of gearing permit performance levels which are impractical by any other means.

They are thin compared to their diameters and are shaftless. Another design features a printed-circuit armature with permanent-magnet field resulting in an output shaft similar to the conventional design but still having the large diameter and thin cross-section.

This type of direct-drive design is also made in A-C servomotors. The motors are furnished with a high-resistance rotor and have linear servomotor characteristics. When used as torquers, they are not expected to rotate very much, for their primary purpose is to provide controlled torque for small angular movements.

The large stator diameter allows a wide selection of speed ranges.

Often a direct conflict exists between the application of an AC or DC torquer. While the d-c pankake motor surpasses the a-c in torque per watt and torque per cubic inch, there are still many advantages of having an AC motor, such as eliminating the brushes and commutator. In many cases, the moderate increase in size and weight is more than offset by the advantages of eliminating commutator brush rigging, need for changing brushes, brush bounce on vibration and radio interference from sparking brushes.

The more powerful units are apt to be made with squirrel-cage rotors. Units in which extreme smoothness of starting torque is required are sometimes made with solid iron rotors.

(2) A-C Servomotors

The most popular type of general-purpose two-phase servomotor uses a low-inertia, high-resistance squirrel-cage construction specifically designed for servo use. But for specific applications, some of the types discussed below are superior to the squirrel-cage motor.

In the drag-cup motor, the rotor conductors are formed into a drag cup of conducting material rotating in the airgap. The slotted-rotor laminations are replaced by a set of stationary iron-ring laminations that provide a low-reluctance path for the magnetic flux. This type of motor is noted for uniformity of developed torque with rotor angular position, freedom from cogging and slot effects, and low bearing friction resulting from the absence of radial airgap forces on the non-magnetic rotor. However, the requirement for relatively large airgaps has resulted in low torque per watt in the smaller sizes of drag cup units. Thus they are used primarily where uniform torque and minimum bearing friction are necessary.

As a compromise between the high performance of the squirrel-cage motor and the uniformity of the drag-cup unit, some small servomotors use rotors of pure unlaminated iron. Although the over-all torque per watt input may be 20 percent less for the solid rotor than for the squirrel cage, these units are sometimes used to obtain smooth performance, low control starting voltage, and reduced manufacturing costs.

Other varieties of mechanical designs include: closed stator slots, with stator coils machine-wound from the outside to reduce winding costs; articulated stators, another way to permit use of machine wound coils on a separable stator; separate rotor and stator sections, so that the rotor and stator can be designed into a user's equipment; and inverted motors, where the rotor assembly rotates around the outside diameter of the stator.

(3) Step-Servo Motors

When energized by d-c voltages in a programmed manner a step-servo motor indexes in given angular increments. Its angular displacement is either clockwise or counterclockwise and is determined by the sequence in which the windings are pulsed.

There are basically two types of step-servo motors. The first works on the reaction between an electromagnetic field and a permanent magnet. This type is classified as a permanent magnet step-servo (PM). The second type works on the solenoid action and is called a variable-reluctance step servo (VR). This unit works on the reaction between an electromagnetic field and soft iron rotor.

The stepping angle is determined by the design but cannot be greater than $\frac{2\pi}{3}$ and still have directional characteristics and uniform motion. It is possible, size permitting, to make the steps any value $\frac{2\pi}{n}$ where $n \geq 3$.

High speed switching by means of solid-state devices has accelerated the growth of step servo motors. D.C. power now can be converted directly into precise rotational motion in synchronism with the input signal.

The use of the correct step-servo is determined by load conditions and performance required. The choice of which to use is governed by the following basic rules.

(a) Permanent magnet (PM) step-servos should be used when:

1. Nonambiguity is desired.
2. Large stepping angles are desired.
3. Pulse rate is low (300 pps maximum bidirectionally)
4. Magnetic detenting is desired.

The choice of the correct PM step-servo is determined by the load, pulse range and power available.

(b) Variable reluctance step-servos should be used when:

1. Pulse rate is high (1200 pps maximum bidirectionally)
2. Ambiguity of position is unimportant
3. Small angular output steps are desired (thereby eliminating (or reducing gearing).
4. Magnetic detenting is not desired.
5. Presence of magnets is not allowed.

The choice of the correct VR step-servo motor also is predicated on the same factors as a PM step-servo. It is important to realize that these are not fixed rules. Specially-designed step-servo motors can have characteristics common to both classes. When a commercially available unit cannot be used, a new unit can be designed integrating the desired features of both classes.

Step-servo motors and their accompanying logic circuitry comprise a basic step servo system. Some advantages of these systems are:

1. Response is the fastest available of any inductive device today (in the order of 1 millisecond).
2. High resolution accompanied by high sweep rates.
3. No hunting or oscillation.
4. As straight digital devices, the need for digital-to-analog voltage conversions is eliminated.
5. Can be used as open-loop servos.

5. TELEVISION SYSTEMS

a. General

A television system will be required in conjunction with the optical pickup in order to amplify and relay the imagery to the final display system. The television link provides a very flexible means (at the present time the only practical method) for connecting the optical pickup system and the display device. In addition, superposition and insetting techniques may be employed to provide a composite display consisting of imagery from several camera sources. Other special electronic effects, such as limited distortion correction and simulation of atmospheric haze conditions, are possible.

The television system considered for this application must have a high resolution capability in order to provide sufficient detail for wide angle visual system requirements. Also the system signal to noise ratio must be high - preferably better than 40 db, in order to achieve an essentially noise-free display. Optimization of other system parameters such as flicker, tone reproduction (contrast range), response to visual scene motion and brightness is required in order to obtain the desired high quality visual display.

A complete television system consists of the camera, camera control electronics and the display device - either a direct-view monitor or a projection system. The television pickup tube employed in the camera is the transducer which converts the optical system inputs to electrical signals and hence is one of the most important components of the entire visual simulation system.

b. Television Pickup Tubes

(1) General

Many types of pickup tubes are presently available for use in closed circuit television cameras and considerable continuing effort is being expended toward advancing the state of the art in camera tube technology. Careful consideration of the characteristics of the various tubes is therefore required in order to help establish feasible overall visual system performance capabilities as well as to determine the optimum choice of a tube or tubes as the case may be.

(2) Vidicon

The vidicon is one of the most frequently used camera tubes in closed circuit television. This tube type is available in 1/2, 1, 1-1/2 and 2 inch sizes with the 1 inch category containing the largest number of different types. The limiting resolution capabilities of these tube types vary from 500 TV lines for the 1/2 inch tube to about 2000 TV lines for the 2-inch tube with corresponding intermediate values for the 1 and 1-1/2 inch tubes. The photocathode highlight illumination requirements vary from a minimum of .1 foot candle (maximum sensitivity operation) to a maximum of about 10 foot candles. One foot candle is a reasonable average value for most standard vidicons. Generally the two larger tubes require higher illumination than the smaller tubes. These vidicons, except the 2-inch tubes, are available with either magnetic or electrostatic focus and the 1/2 and 1 inch are available with electrostatic deflection. The 1-1/2 and 2 inch tubes are generally available only with magnetic deflection. These tubes are readily available both in standard and ruggedized versions. They may be mounted in any position, are relatively small, light in weight, are not excessively expensive and have a fairly long useful life. Most high resolution closed circuit cameras presently manufactured employ either 1 or 1-1/2 inch vidicons. The 1/2 inch vidicon cannot meet high resolution requirements and will not be considered further.

(3) Image Orthicon

A second type of camera tube which is often used in television cameras, particularly studio broadcast cameras and cameras for use in televising scenes with a very low illumination level, is the image orthicon. This tube is available in 2, 3, and 4-1/2 inch sizes and is one of the most sensitive of the presently available pickup tubes. For example the 3-inch image orthicon type 7967 is capable of a limiting resolution of about 600 television lines with a photocathode illumination of 2×10^{-5} foot candles and considerably greater resolution at higher light levels. The photocathode illumination requirements vary from a minimum for usable picture of 2×10^{-7} foot candle to an upper requirement of about 5×10^{-2} foot candle. This type of tube with its associated deflection and focus coils is quite large, generally more expensive than vidicon tubes and somewhat limited in operating orientation. It has not attained widespread use in industrial closed circuit television cameras.

(4) Other Types

Although the vidicon and image orthicon are at present the most widely used tube types, several recently announced improvements appear to offer potential advantage. Among the new developments is the Amperex PLUMBICON, a vidicon type tube available in a one-inch size. This tube has a lead-monoxide photo conductive layer which eases lag, dark current and sensitivity problems associated with conventional vidicons.

The secondary electron conduction vidicon (SEC) from Westinghouse is another fairly recent development which offers promise. This tube presently is available with magnetic deflection and focusing which make the tube about the same physical size as a 3-inch image orthicon. However, work is proceeding on an electrostatic version which will considerably reduce its size. Outstanding characteristics of this tube are its low lag, very high sensitivity (several hundred times more sensitive than a standard vidicon) and wide dynamic range.

One inch, 1-1/2 and 3 inch image dissector camera tubes with aperture sizes down to 0.0005 inch have been recently made available. These tubes have a high resolution capability, non-storage operation, wide linear dynamic range and long life. However, present sensitivity limitations preclude their use at high resolution television scanning rates.

Announcements by General Electric of the focus projection and scanning (FPS) vidicon and an electrostatic image orthicon are important new additions to the camera tube field.

c. Camera Tube Characteristics

The television camera pickup tube accepts the visual data from the optical pickup and provides the electrical signal to the display system, hence its parameters are of vital importance to overall system performance. The tube characteristics influence both the optical and electronic systems design approach and in some cases may be the limiting factor. The important television pickup tube characteristics are listed below:

1) Mechanical

   a) Physical envelope dimensions
   b) Effective Photocathode Diameter
   d) Weight
   d) Mounting position

2) Electrical Requirement

   a) Focus
   b) Deflection
   c) Alignment
   d) Heater power
   e) Electrode Voltages

3) Sensitivity

4) Spectral Response

5) Resolution

   a) center
   b) edge
   c) Dynamic focus

6) Dynamic range and gray effects scale

7) Signal to noise ratio

8) Lag or Persistence

9) Gamma

10) Environmental

    a) Ruggedness
    b) Temperature effects

Appendix H lists some of these characteristics for several commercially available tubes. General discussion of these parameters and their effects on television system performance is given below.

The physical dimensions of the pickup device or camera are determined essentially by the choice of tube and the need for packaging all the electronics in the camera (i.e., a self-contained camera). Assuming in all cases that the camera is self-contained it is apparent that the 4-1/2" image orthicon, magnetically deflected and focused, will require the largest package (volume and weight) with correspondingly smaller cameras down to the smallest for a one-inch electrostatic vidicon. The physical construction of the tube may prohibit use of the tube in a face-down position due to flakes or specs of material droping on the photo-sensitive surface causing them to "appear" in the TV display. This is particularly true if vibration is encountered. The photocathode diameter affects the resolution capability of the tube.

Deflection and focus techniques affect the resolution and power requirements of a tube. Magnetic deflection and focus require maximum power to operate; however, highest resolution is obtained for this mode of operation. Hybrid tubes, generally vidicons, consisting of electrostatic focus with magnetic deflection, reduce focus power requirements to nearly zero while reducing the magnetic deflection power by a factor of about five. Resolution is reduced 15-25% in the tube. All electrostatic tubes (electrostatic deflection and focus) require very low power but suffer reduction in edge resolution as compared to the hybrid tube. Eliminating deflection and focus yokes significantly reduces weight and size of a camera. Also resolution improvements can be obtained by use of special yokes and by increasing the focus field strength and/or certain electrode voltages to values higher than those normally given by the tube manufacturer. Dynamic focusing is usually used to improve edge resolution.

The pickup tube sensitivity and spectral response determine the incident light level and frequency content required for tube operation at specified picture quality. Tube resolution, dynamic range (gray scale) and signal-to-noise ratio determine picture quality. Resolution defines the number of resolvable elements in the picture. Dynamic range determines the range of brightness levels the tube can reproduce, commonly called gray scale rendition. The signal to noise ratio provides a measure of the relative noise present in a video signal, and is generally specified as peak to peak signal to RMS noise for pickup tubes. Signal-to-noise ratio affects the gray scale reproduction capability of the tube and also can degrade resolution. This ratio is determined primarily by the performance of the video preamplifier connected to a vidicon while the internally generated noise in an image orthicon is the main factor in determining its signal-to-noise ratio.

Lag or image persistence is a measure of the image signal retention from frame to frame. This is not a serious problem if very little motion is occurring in the scene. However, as motion becomes faster lag will cause smearing of the moving object and loss of resolution. Vidicons are more subject to lag than are other types of pickup tubes normally used in television.

Gamma is the slope of the pickup tube light transfer curve. The pickup tube transfer curve is one of several required for overall TV system transfer evaluation (i.e., amplifier transfer curves and picture tube curve, for example).

If extreme environmental conditions are encountered it may be necessary to ruggedize the pickup tube or to provide cooling or other special provisions in order to obtain acceptable performance.

SECTION IV - DESIGN CRITERIA

1. GENERAL

Appendix F is a preliminary specification for a family of optical pickup systems which will provide significant advances in the current state of the art. As mentioned in Section I, the best currently available optical pickups operate with approximately 60-degree fields of view. These are considered the reference design in this study because of their overall performance. Wider fields of view (up to 98-degrees) are available on other single-objective systems but they suffer quite appreciably from distortion due to the design of the objective lens and a lack of "built-in" compensation.

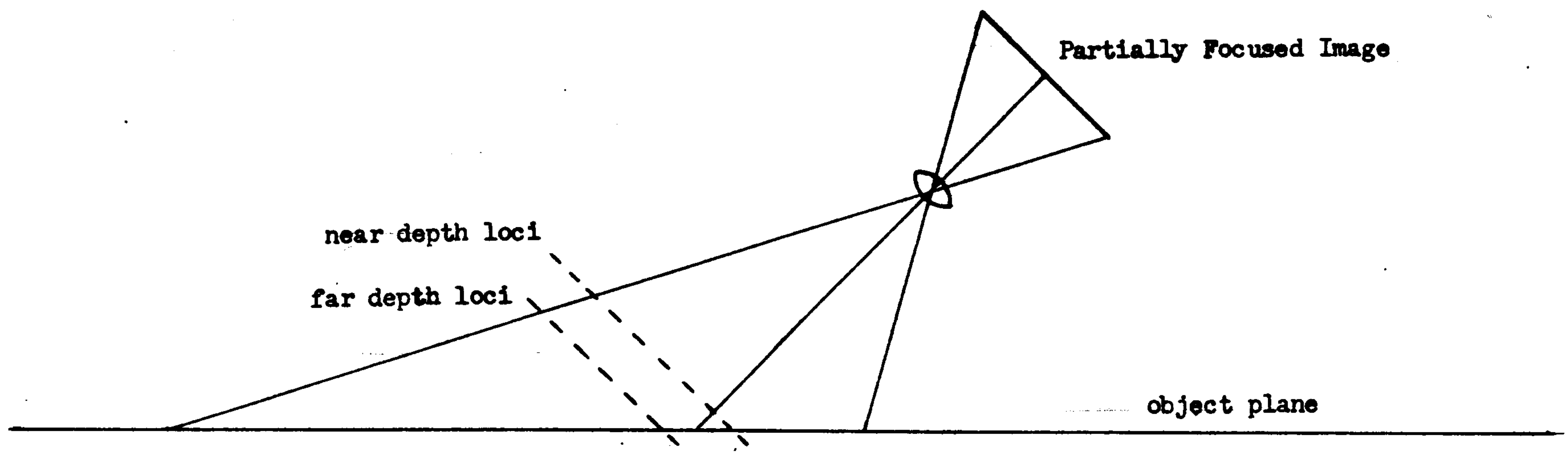
The specification does not attempt to define an exact field of view because specification-wise, distinguishing between numerical values does not represent any great difference. The points of demarcation between the single-objective (wide angle) and ultra-wide angle approaches have been well defined elsewhere in this report as has GAC's belief in the superiority of the wide angle oblique optics system as both an initial advance and as a basic building block for early field angle increases. Working distances are optimized with this approach regardless of field angle requirements, and motion system complexity remains relatively low even into the ultra-wide angle range. Vertical optics systems represent a next state-of-the-art advance. The following paragraphs, together with Appendices G and H describe some of the specific basic design techniques plus information on related servo and television equipment which are germane to the above basic conclusions and recommendations of the study.

2. FEASIBLE TECHNIQUES

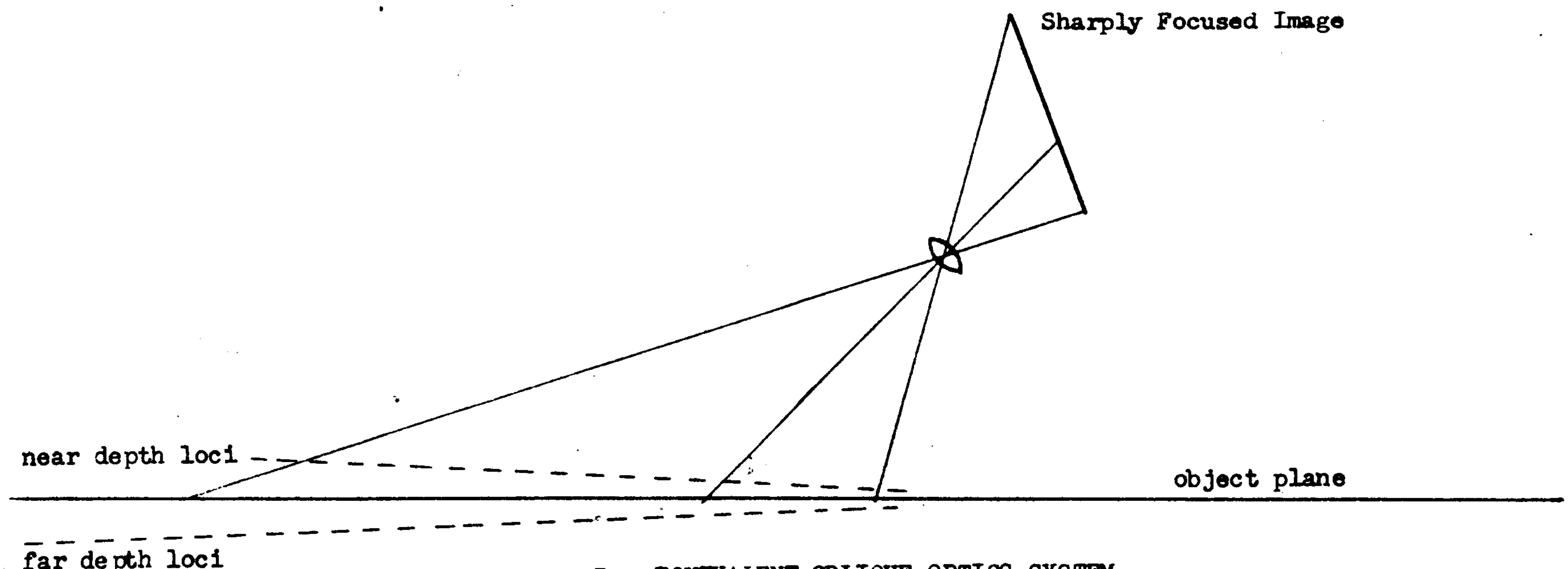
a. Oblique Optics

Most optical pickups used in visual simulators operate such that the optical axis is either parallel to the model surface or at some angle considerably less than 90 degrees to the model surface. Conventionally an optical image plane is recorded normal to the optical axis to preclude distortion of the object data; but the amount of object information sharply focused in the image plane is small because of the narrow axial depth of field. Figure 10A shows a 16 mm, f/10 lens with a 60-degree field of view oriented 45-degrees to the object surface at a height of 1.4 inches. For the purpose of illustration, we assume a circle of confusion of 0.002 inches (this is somewhat larger than that typically used with a one inch vidicon). The near depth of field is 1.81 inches and the far depth is 2.07 inches. This results in a total depth of field at the object plane of only one half inch along the optical axis, although the 60-degree lens is capable of viewing four inches of object plane data across the field.

The effective depth of field can be greatly increased if the image plane is inclined to the optical axis as shown in Figure 10B. Under these circumstances, both the object and image conjugate distances vary across the field so that all the data that the lens is capable of gathering is sharply focused in the oblique image plane. It can be shown that a line extended from this image plane passes through the point described by the intersection of the entrance pupil and the object plane. Using the parameters described above, the near depth of field varies from 1.22 inches



A. CONVENTIONAL SYSTEM

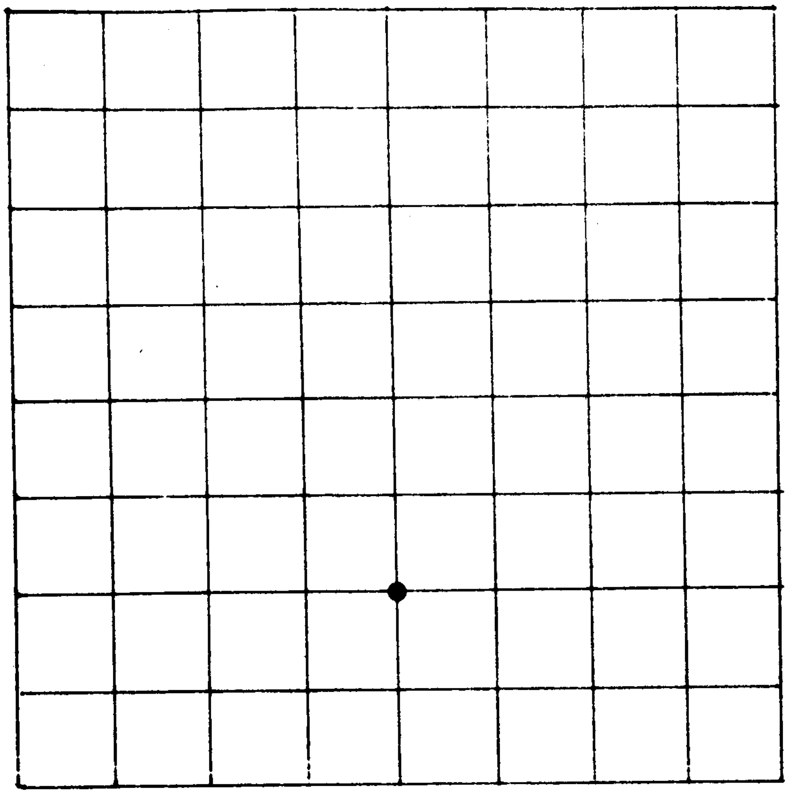


B. EQUIVALENT OBLIQUE OPTICS SYSTEM

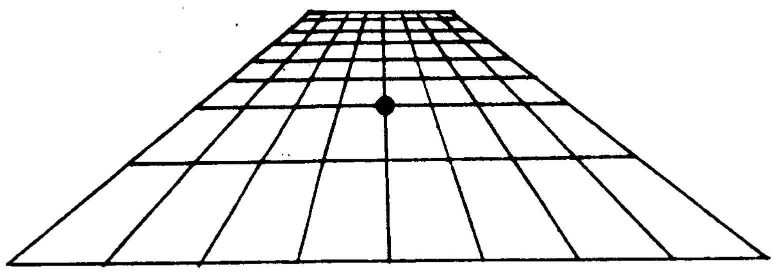
FIGURE 10 - COMPARISON OF IMAGE SYSTEMS

to 3.42 inches along the optical axis and the far depth varies from 1.31 to 4.81 inches. This results in an infinite depth of field along the object plane.

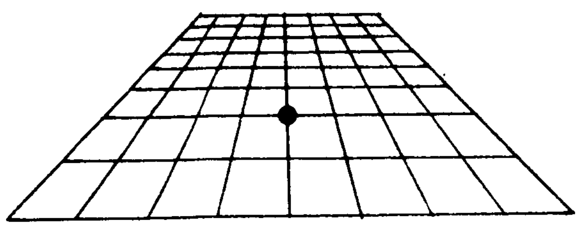
Although an effectively infinite depth of field is attained, distortion is present due to the resulting magnification variation over the field of view. Figure 11Ais a plan view of a grid on the object surface. Figure 11Bis the image of the grid using the oblique image plane. The image of the grid is over magnified for near object data and under magnified for far object data. Part C of Figure 11 shows the undistorted geometry obtainable with a conventional system.



A. PLAN VIEW OF OBJECT



B. IMAGE FORMED ON OBLIQUE PLANE



C. CORRECT PERSPECTIVE VIEW

FIGURE 11 - OBJECT-IMAGE CONFIGURATIONS

b. Multiple Pickup Tube System

Another technical approach to the problem of infinite depth of field is the multiple pickup tube system, using two or more photocathodes. Figure 12 illustrates the principle of this approach. A single objective lens operating at low f/numbers (f/4 to f/6) sharply focuses the model data on a plane oriented at some angle to the optical axis. This image plane can be thought of as a number of non-coplanar image planes which are perpendicular to the optical axis. For the sake of discussion, let us consider three such planes located at three different longitudinal positions. By use of beamsplitters, we can assign a photocathode to each of the three planes. Each pickup tube has its own set of supplementary optics to insure proper perspective. Although each pickup tube receives data from the entire field, only the high-resolution data on each of the three planes is recorded on each photocathode. The remainder of the data is eliminated by masking the tubes. The problem reduces to using only the high-resolution data from each of the tubes and recombining this data into a single video signal suitable for presentation to a display system. Figure 13 is a simplified block diagram of how this can be done. Each of the pickup tubes of cameras A, B and C has the scene imaged on its photocathode surfaces. It can be assumed that the high-resolution portions of the imagery on the three tubes occur as shown in Figure 14 . This imagery is segmented to be parallel to the scan lines (standard TV scan format) that read out the data. The video output from each camera is fed to a switch that applies

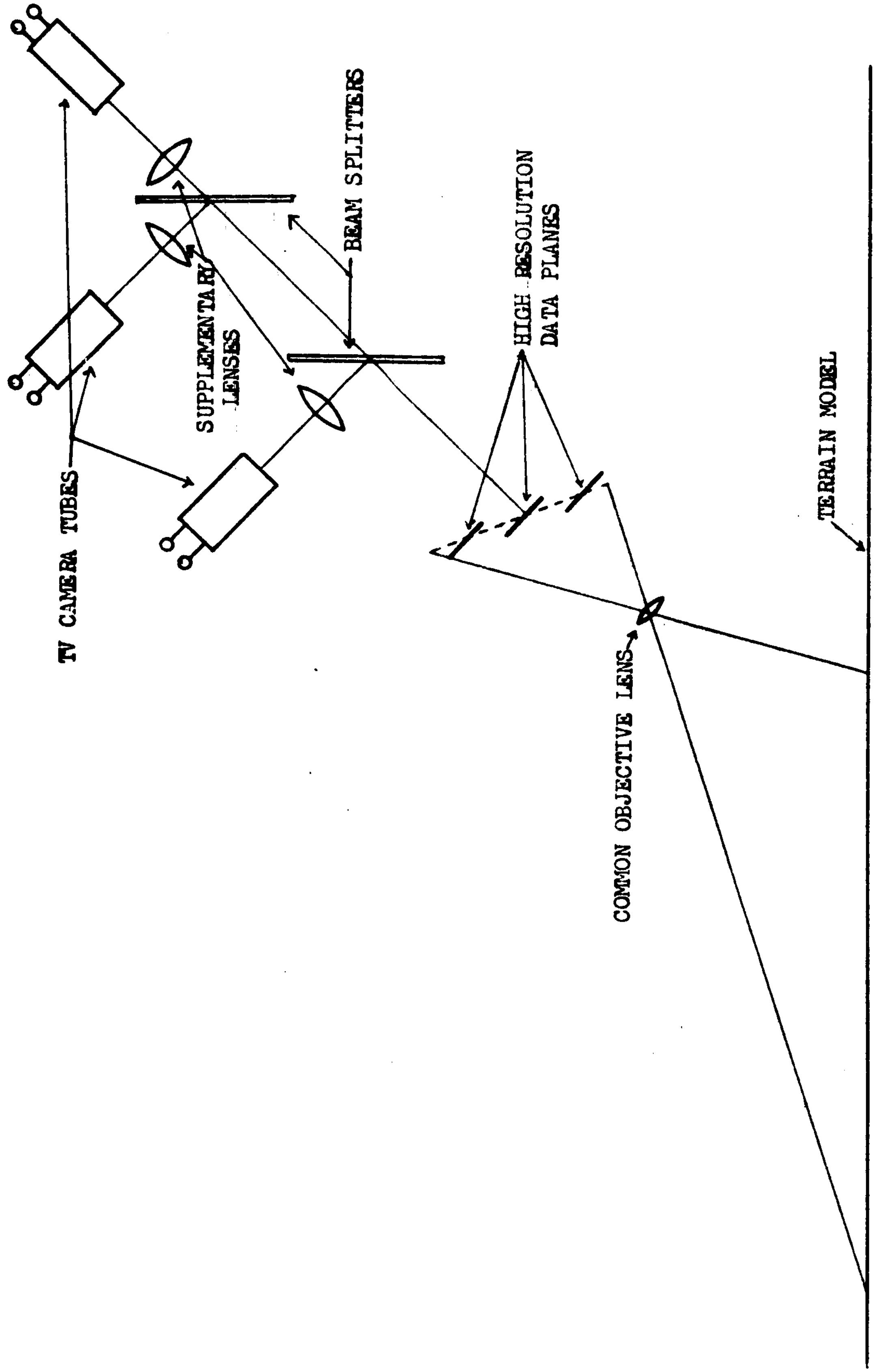


FIGURE 12 - MULTIPLE PICKUP TUBE SYSTEM

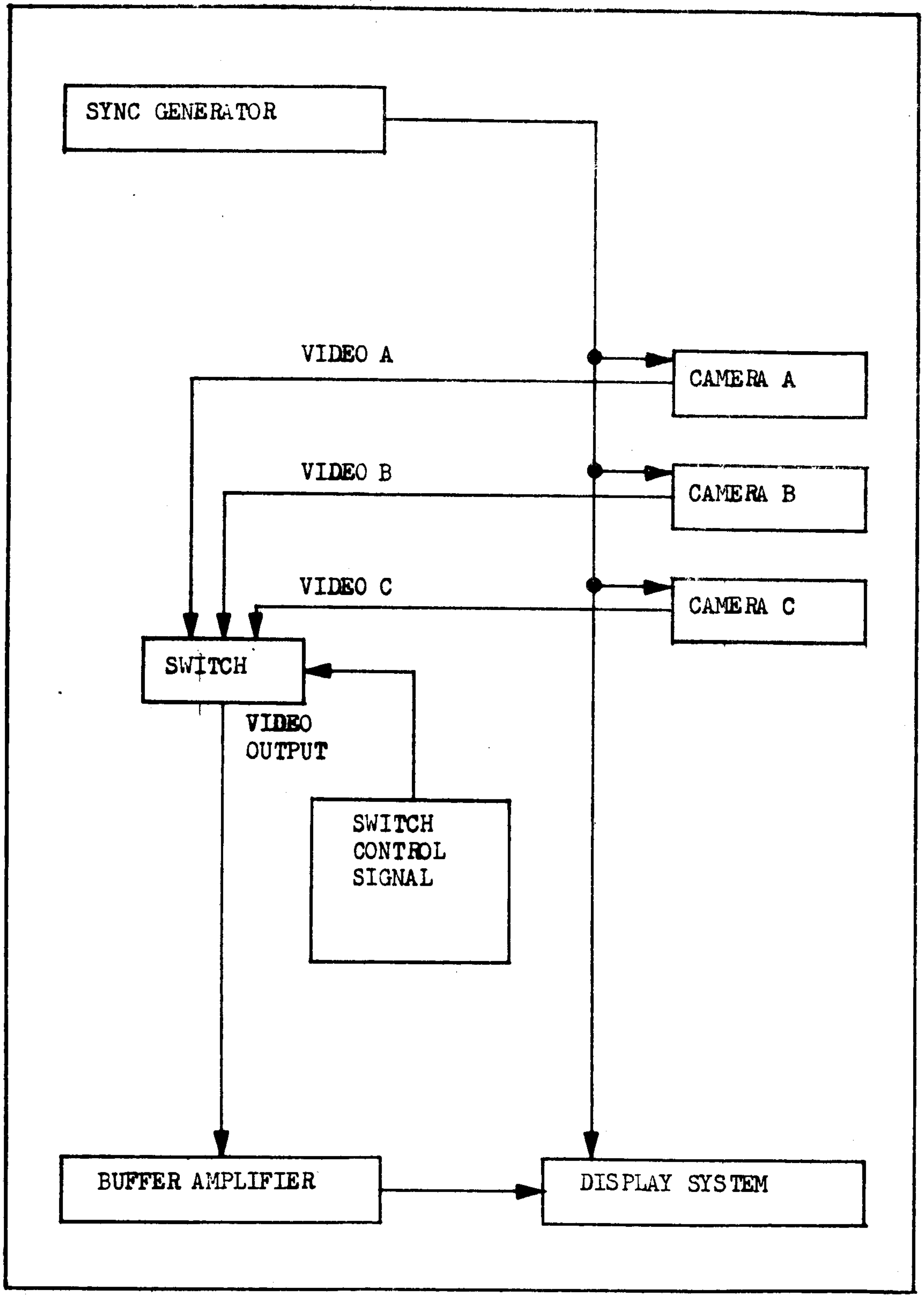
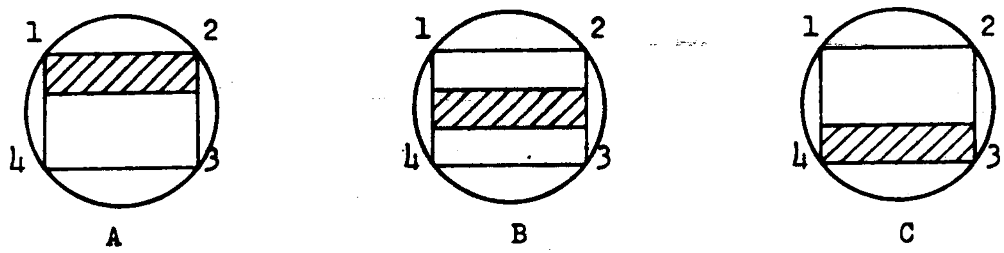


FIGURE 13 - MULTIPLE TUBE SYSTEM BLOCK DIAGRAM



Notes:

1. Scanned Area of Photo Cathode Defined by Rectangle 12341
2. High Resolution Imagery
3. Low Resolution Imagery

FIGURE 14 - PICKUP TUBE DATA

video A, B, or C to the buffer amplifier, depending upon the switch control-signal input. The output of the buffer amplifier supplies the video signal to the display. Since a common sync generator is driving the cameras and display system, the scanning sweeps of all units are in synchronism. If the switch is activated during the horizontal retrace time of the system, it is possible to select the output of any pickup tube for the display and to switch between pickup tubes without causing display discontinuity. Switching can be arranged so that the high-resolution video data is always continuously sent to the display system.

The switch control signal can be derived from a computed signal, since knowledge of optical pickup head details and attitude orientation would permit calculation of the break points on the camera tubes between the high- and low-resolution data. However, it would simplify the process if the switch control signal were generated from the pickup tubes; controllable masking of the face of each pickup tube will permit generation of video signals that will drive simple logic circuits to activate the switch.

The system described above is based on the assumption that the high-resolution data on the camera tubes are always segmented parallel to sweeps; however, as pickup head angular motions become larger, this assumption no longer is valid, since nonparallel segmentation now will occur. This requires more complex switching since the video switching occurs during the active time of a sweep line.

This problem can be solved by (1) optically maintaining the parallel-segmented high-resolution data and (2) the application of state-of-the art high-speed logic and switching circuits. Additional techniques can be formulated for switch-control signal generation by the camera tubes themselves to minimize the requirements for external computation and signal inputs.

77.10 (5-63) REF: ENGINEERING PROCEDURE S-017

c. Multiple Objectives

More than one objective lens may be considered for solutions to problems with either wide angle (between 60 deg. and 120 deg.) or ultra-wide angle (greater than 120 deg.) simulated fields of view. The value of a multiple objective system might be questioned for wide angle applications, as the advantages in performance would have to offset the increased costs, added complexity and presently-anticipated restrictions on maneuverability.

Using this approach for ultra-wide angle pickup devices however, appears quite valid since such systems would require several pickup tubes anyway in order to maintain acceptable angular resolution over the resulting total field of view.

A multiple objective lens approach is approximated by effectively combining two or more optical pickup devices together for use as a single pickup system having a common entrance pupil. Individual optical systems are required to operate independently with their own pickup tubes. Complexity can be minimized by interconnecting mechanical and/or electrical linkages and utilizing the same servo signals for inputs to the individual systems.

The objective lenses share a common entrance pupil position to maintain correct geometric perspective for the individual objective lenses. Path-folding optics precede the objective lenses such that extreme field rays traced back from the object space converge at a common point (i.e., the system center of perspective). Each of two or more objective lenses is used to yield high-resolution performance over moderate fields of view. These fields of view may individually cover moderate angles of 40 deg. to 60 deg. The use of multiple objective lenses and separate pickup tubes overcomes two of the most basic problems in pickup devices:

1) Optical limitations are controlled through limited angular coverage.
2) Net system resolution is now high and equal to that provided through any individual channel.

Note however, that considerable care must be exercised in both the electronic and mechanical design in order to obtain and maintain accurate alignment and registration of the final mosaicked electronic image and resulting display.

Complex mechanical design problems exist, since angular motions of the pickup cannot be simulated optically. Because the total field of view comprises the fields of view from both objective systems, the rotation of simple optical elements cannot simulate angular motion as is done in present single objective systems. Electronic simulation of these motions is extremely limited and imposes additional problems such as noise and stability. Pitch, roll and yaw can be simulated by the rotation of the entire pickup system about the entrance pupil. One such means of doing this is shown in Figure 15 . The pickup system is mounted on three rails, the center of curvature of each being coincident with the common entrance pupil point. Each attitude motion is servo controlled. The entire gimbal system is mounted on a bridge assembly to move in X, Y, and Z.

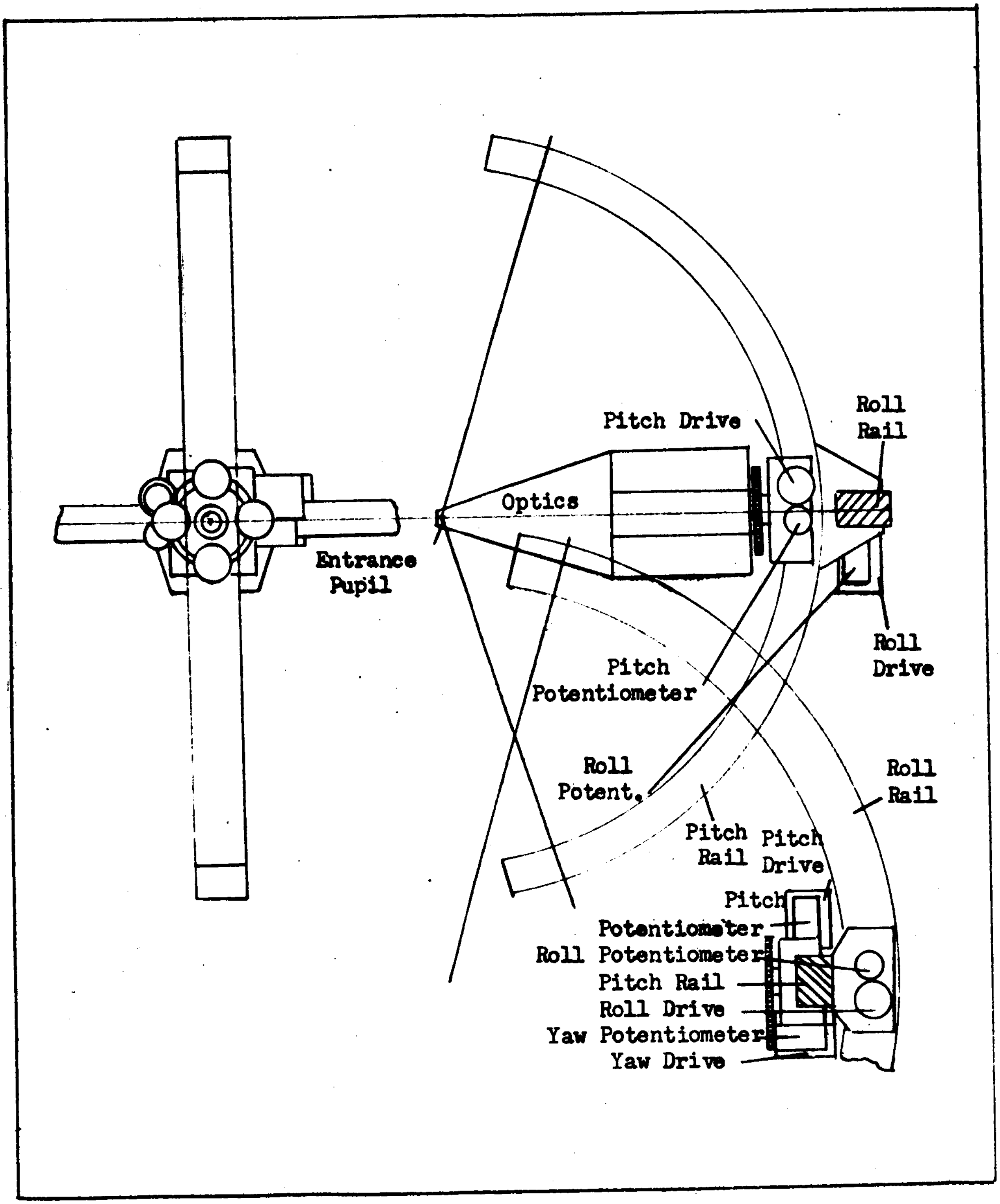


FIGURE 15— CAMERA GIMBAL SCHEME

The mechanical design must also permit system adjustments for alignment purposes, yet be capable of maintaining this final alignment during all maneuvers. Precautions such as parallel driving of pickup and playback tube deflection yokes; highly stable amplifiers; common regulated power supplies; and master as well as individual centering, trim, etc. controls will aid in maintaining an electronically stable display.

d. Vertical Optics

Another approach to the problem of attaining an ultra-wide angle optical pickup incorporates a single objective lens and a multi-channel television system. The ultra-wide angle objective (field of view in the vacinity of 180 degrees) is oriented with its axis always perpendicular to the terrain model datum. A number of pickup tubes and supplementary optics are positioned about the image surface of the objective system such that each tube receives data from only a portion of the total image. These fields of view overlap to insure continuity at the raster edges of each pickup tube. Electronic correlation eliminates the overlap in the display field. The pickup is positioned to simulate altitude and planemetric location. Angular motions can be simulated by rotating the entire pickup about the entrance pupil or by re-positioning the individual pickup tube.

This technique appears to offer the least return in terms of procurement dollar cost and operating complexity. Also if a dioptric lens system or a catadioptric system having a first reflective convex surface is used, the problem of an internal pupil immediately limits the optimization of working distance. Catadioptric system with external pupils are, on the other hand severely limited by angular motion and general data transfer restrictions.

3. RECOMMENDED OPTICAL DESIGN

Figure 16 is an optical schematic of the recommended design. It consists of a refractive system with a 110 degree field of view employing the inclined image plane concept and a means to correct distortions.

The optical probe schematic embodies such features that if manufactured it would represent a significant state-of-the-art advancement in optical pickup devices. Two items of major significance make this probe unique. The probe operates at low f/numbers (approximately f/6) and at the same time images high resolution data over the full format of the pickup tube.

It should be noted that previous designs of optical probes depended on "stopping" the lens down until lighting requirements became unwieldy or resolution losses too severe or both. Lighting requirements actually posed a thermal problem requiring means to dissipate the heat buildup before the models melted. The lenses were stopped down in the region of f/20 to f/30 for vidicons and f/40 to f/60 for image orthicons. Even at these f/nos. the depth of field problem existed. The resolution limitations at these apertures sometimes precluded even theoretically-perfect lens designs (diffraction limited systems) from offering the desired resolution.

In compliance with the specified goals of this program the optical probe schematically illustrated offers the following potentials:

1. An effective depth of field which is infinite.
2. Maximum angular coverage without special pickup tubes or display systems

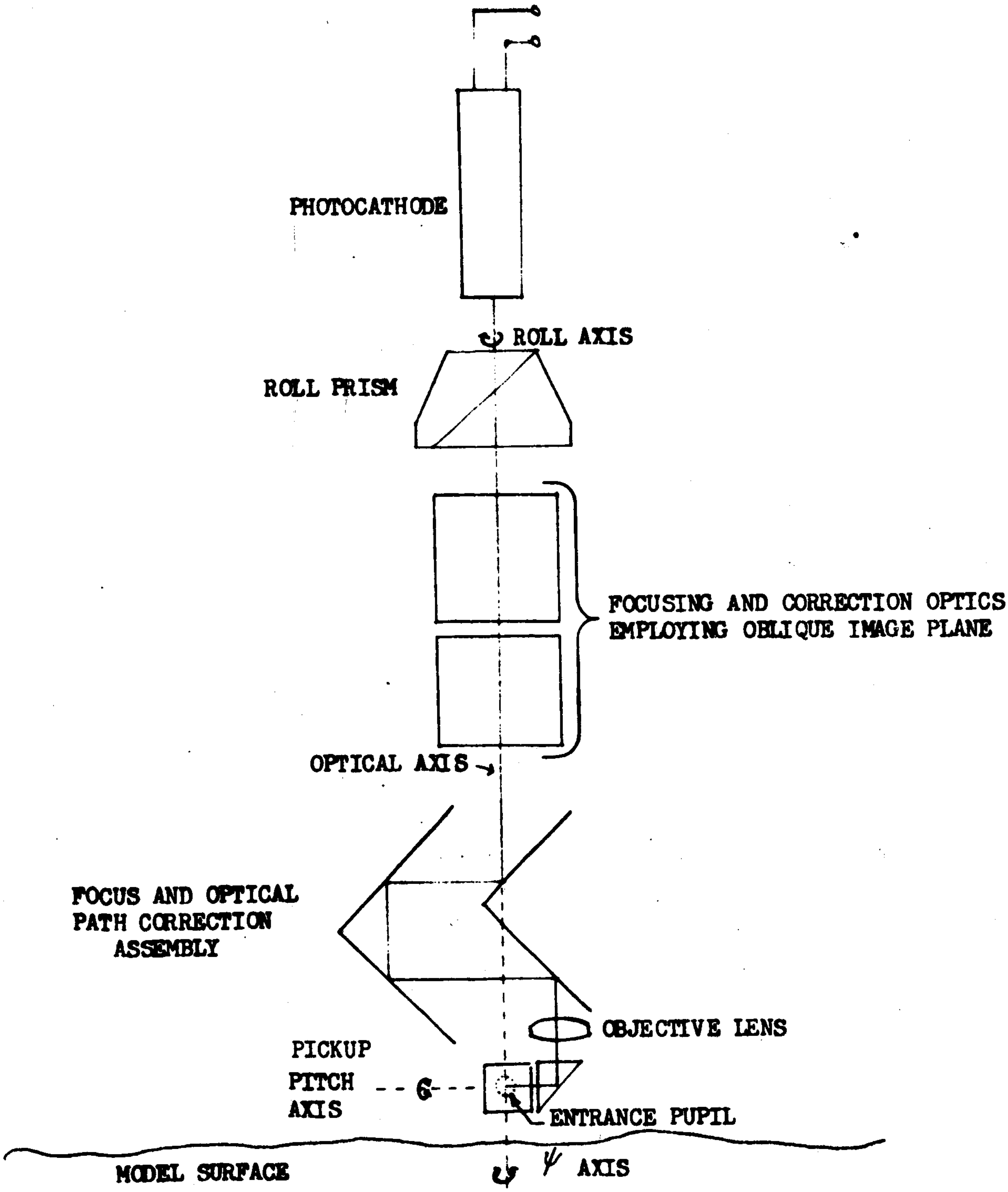


Figure 16 . OPTICAL PROBE SCHEMATIC

3. A model working distance that will allow significantly-smaller model scales to be used

4. The full six degrees of freedom with minimum constraints on realistic angular motion requirements

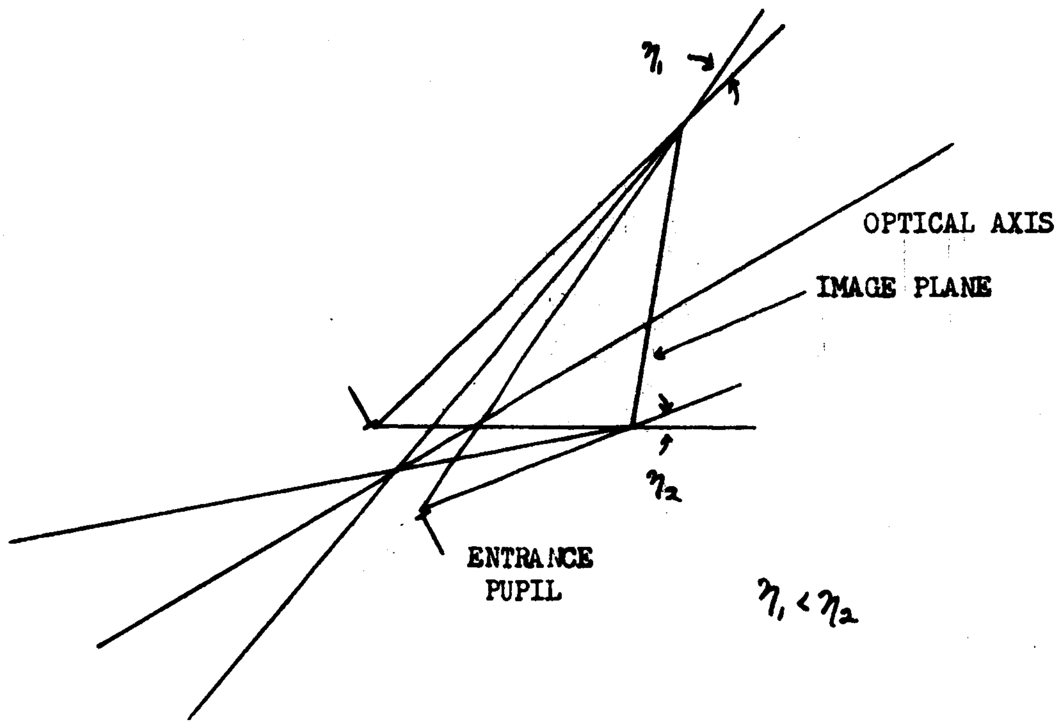
Closeness of approach to the model with this system is approximately .050 to .060 inches. This is determined by the distance the entrance pupil is from the model surface at closest approach. Since the entrance pupil (center of perspective) is located inside the first of a dual prism arrangement the closeness of approach is dependent on the prism size needed for the desired entrance pupil diameter and location. Depending on the type of vehicle to be simulated the entrance pupil would be located at model scale dimensions from the center of gravity (pickup pitch axis).

a. Objective Lens

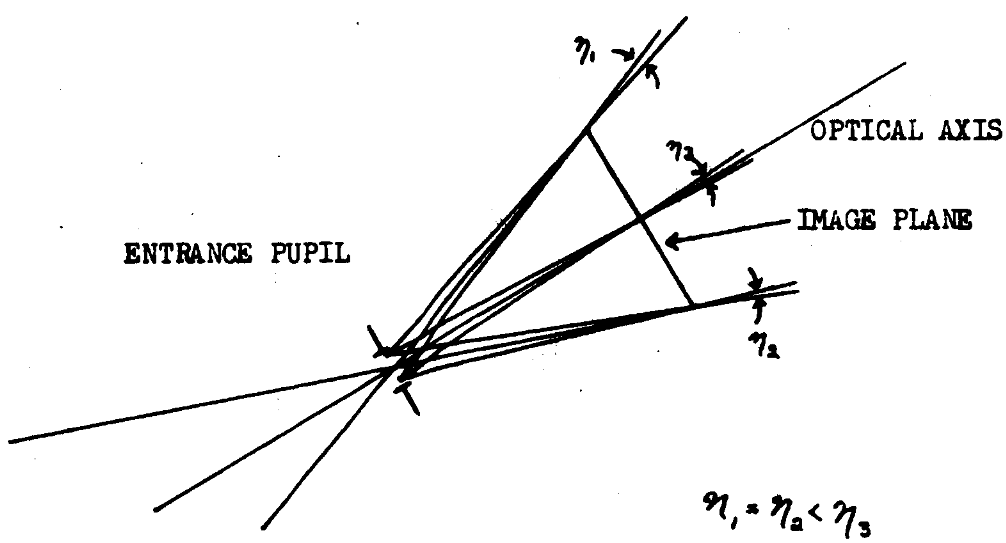
The objective lens is located just beyond the second prism. It is a multi-element lens similar in design to a microscopic objective lens. An eyepiece-type of lens might also be applicable. Depending on the objective lens design, selected corrections to the resultant image will have to be included in the focusing and correction optics assemly.

b. Aperture Compensation

Figure 17 illustrates the geometric relationships of the image-forming process in the conventional manner. Aperture vignetting occurs in a symmetrical fashion and is a function of field angle.



A. INCLINED SYSTEM



B. CONVENTIONAL SYSTEM

FIGURE 17- IMAGING PROCESSES

In figure 17B angle η_3 represents the central unvignetted cone of light forming an image on axis. Angles η_1 and η_2 are equal and less than η_3. They represent image-forming cones of light which are angularly displaced the same amount from the optical axis. Linear distance changes between the entrance pupil and the object produce magnification changes which increase or decrease angles η_1, η_2, and η_3. In the conventional system the relative change of these cone angles with respect to each other is generally negligible. The absolute change in these cone angles for various object distances however, cannot be ignored-especially for close object distances (model to lens working distances). The importance of these relations is given by the following formula:

$$E = \frac{t\ B}{4\ (\ f/no.\ )^2 (\ 1 + m\ )^2}$$

where: E = illumination at the image plane (footcandles)

t = transmission of the optical system ($t < 1$)

B = object brightness (footlamberts)

f/no. = relative aperture of the optical system

m = magnification

As mentioned previously, conventional systems must employ high f/nos. in order to gain depth of field. This factor coupled with the effects of magnification severly limit the useful energy contributing to image formation.

Coupled with the energy losses are the limitations imposed on resolution. Using the criterion of perfect image formation based on diffraction limited performance the resolution of an optical system (circular aperture) is given by the formula:

$$R = \frac{1}{1.22\,\lambda\ (\ f/no.\ )}$$

Where: R = resolution (lines per mm or lines per inch)

λ = wavelength of light (mm or inches)

Figure 17A represents the same geometric relationships (angles of view, lens to model distance, etc.) as in figure 17B but now the concept of the inclined image plane is used.

Aperture vignetting still occurs (generally this is a characteristic of all optical systems) but the rotational symmetry of the conventional system is only a special case under certain conditions when the inclined image plane concept is used. In the inclined image plane angles η_1 and η_2 are not equal. The inequality of angles η_1 and η_2 does not remain constant but varies over a wide range. Dynamic compensation will have to be made for this condition.

Although a penalty must be paid in vignetting compensation the advantages gained by using the oblique image plane more than offset these secondary effects. As illustrated in figures 17A and 17B the entrance pupils for the two systems are quite different in size with the oblique system being approximately four times larger. Referring to the equation the illumination potential would increase approximately eleven times. The equation yields a fourfold increase in resolution. These advantages greatly offset the difficulties of implementing the concept into working hardware.

c. Focussing

The focusing and optical path correction assembly performs two basic functions. One function is to realign the optical axis to pass through the simulated vehicle center of gravity and the other is to provide a means of changing the objective lens focus without moving any lenses. This is done as shown in Figure 16 by moving two mirrors or prisms laterally.

d. De-rotation

The prism containing the entrance pupil rotates about the pickup pitch axis. With this particular motion system simulation of vehicle pitch must also employ the use of the roll prism. As the pitch prism is rotated it induces an apparent vehicle roll motion. Proper de-rotation by the roll prism cancels this induced motion and yields pure vehicle pitch. Pure roll is simulated by rotating the roll prism (Pechan prism) about an axis parallel to the optical axis. Vehicle yaw (level flight) is accomplished by a rotation about the ψ or heading axis. Yaw simulation in the presence of pitch requires rotations of the pitch prism, the roll prism and the heading assembly. For heading changes the lower assembly, including all components between the model and the focusing and correction optics assembly, are rotated about the ψ axis.

e. Distortion Correction

In order to present a high quality image at the display end, the recommended optical pickup must be corrected for two inherent distortions. These are: (1) distortion arising from the wide-field-of-view objective lens design; and (2) apparent distortion due to the inclined image plane concept. Both corrections can be made in two major optical assemblies containing spheric and aspheric elements. These elements are positioned for minimum distortions through servo-controlled inputs which automatically vary with vehicle attitude and altitude. The two assemblies view the inclined image plane and relay an undistorted and sharply focused image onto the surface of the television photocathode.

4. ELECTROMECHANICAL DESIGN

a. General

The optical pickup will require a servo system for each of the simulated vehicle attitude motions. In addition, servos will be needed to implement focus, aperture and distortion corrections. Total visual system performance requires that the pickup also be moved (with respect to model terrain) in x, y, and z to simulate vehicle lateral, longitudinal and altitude motions. These latter three motions are performed by servos essentially external to the pickup proper and hence are beyond the scope of this study.

The load requirements of the attitude servos have been determined and desired goals of system performance have been defined. The focus, aperture and distortion correcting servos are well within the current state-of-the art since stringent accuracy, rates and accelerations are not required to perform these functions. Hence, the design feasibility of these servos need not be considered in detail here.

Since the visual effects of vehicle attitude changes will be simulated by the optical pickup it is desirable that the servos be capable of providing angular accelerations, velocities and displacements characteristic of a number of different vehicles. Also the tracking or positional accuracy of each servo system must be held within limits such that pickup pointing accuracy, with respect to the computer attitude command, will meet system requirements.

The following performance characteristics have been selected as design goals for each of the attitude servo systems:

Maximum acceleration - 2 rad/sec^2

Maximum velocity - 2 rad/sec

Displacement - continuous

Positional tracking accuracy - 2 - 3 minutes of arc

The load inertia that each servo must drive is given below.

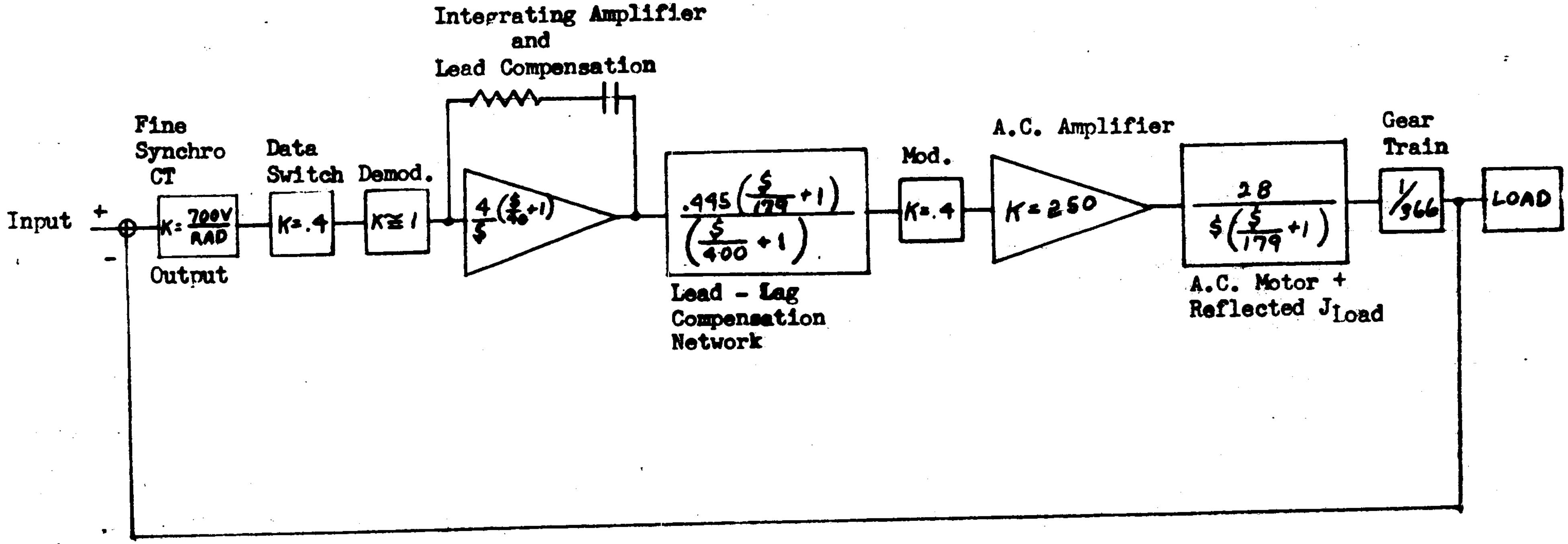
b. System Description

The attitude servo systems are analog using an ac servo with dc com-compensation networks. The accuracy requirements dictate that a Type II servo system be used; with this type system a positional error between input and output occurs only during acceleration. The acceleration error constant K_a based on an effective dynamic error of 1.65 minutes (see Page 97) and acceleration of 2 rad/sec^2 is equal to 4170 sec^{-2} or 72 db. A two speed synchro system is used to provide position feedback.

c. Roll Servo

Fig. 18 is a block diagram of the roll servo. The inertial load for this servo is a glass prism, whose approximate size is 2 inches high, 1.5 inches wide, and 1.5 inches deep, mounted in a rotation assembly. Additional inertia is contributed by the fine and coarse synchro. The total inertial load is calculated to be .031 oz-in sec^2. The structural effect of this load is negligible.

The total torque required to accelerate the load, overcome friction and compensate for gearing efficiency was calculated to be .081 in-oz.



NOTES: 1. Abbreviations

(a) CT - Control Transformer
(b) Demod. - Demodulator
(c) Mod. - Modulator
(d) J_{Load} - Load Moment of Inertia

FIGURE 18 - BLOCK DIAGRAM OF ROLL SERVO

A Kearfott CMO-0132-450 size eight, 26 vac, 400 cps servo motor was chosen. Its characteristics are listed below.

1. No load speed = 7000 rpm $\pm 7\%$.
2. Inertial time constant = .005 sec
3. Stall torque = .34 in-oz $\pm 7\%$.
4. Rotor inertia = .18 gm cm^2.

The motor transfer function of shaft position to applied motor terminal voltage is $\dfrac{28}{S\left(\frac{S}{179}+1\right)}$. The reflected load inertia is included in the lag function $\dfrac{1}{\left(\frac{S}{179}+1\right)}$. The electrical time constant is omitted because it occurs at least four octaves above the motor inertial time constant and will have very little effect on the system dynamics. The calculated motor gain is 28 radians per sec per volt.

Because of the characteristics of the roll prism the image will roll at a rate of twice the prism rate. Therefore, the gear ratio, based on maximum velocity of 1 radian per second and a motor speed of 3500 rpm, is 366:1. The reflected load inertia to the output shaft of the motor is less than the motor armature inertia.

An integrator is needed to provide the additional integration $\frac{1}{S}$ to make the servo loop a type II loop. The integrator gain is 4. The lead compensation $\left(\frac{S}{40}+1\right)$ in the feedback of this amplifier is for loop stability. The lead-lag network $\dfrac{\left(\frac{S}{179}+1\right)}{\left(\frac{S}{400}+1\right)}$ cancels the effects of the motor lag $\frac{1}{\left(\frac{S}{179}+1\right)}$.

This lead-lag network, which has a gain of 0.445 V/V, plus the lead network in the feedback of the amplifier provide the proper phase and gain margin required for a stable loop.

The data switch separates the fine and coarse synchro inputs. It has a gain of 0.4 v/v for the fine synchro input and a gain of approximately 1 v/v for the coarse synchro input. The gain of the fine synchro input signal to the data switch is 700 v/rad.

The demodulator changes the ac modulated carrier signal to dc. This change is required for the compensation networks. Compensation can be achieved more easily at dc than with the modulated carrier ac signal. The gain of the demodulator is approximately 1 v/v.

The modulator changes the dc signal back to an ac signal. Its output is the input to the ac amplifier which drives the ac servo motor. The gain of this amplifier, based on a K_a of 4170 sec^{-2}, is 250 v/v.

The open loop Bode diagram is shown in Fig. 19. The measured gain and phase margin from this diagram indicate a stable loop.

The closed loop Bode diagram Shown in Fig. 20 was obtained from the open loop data and a Nichols chart. The diagram shows that the loop has a bandwidth of 170.0 radians and a damping ratio ζ (zeta) of approximately 0.5.

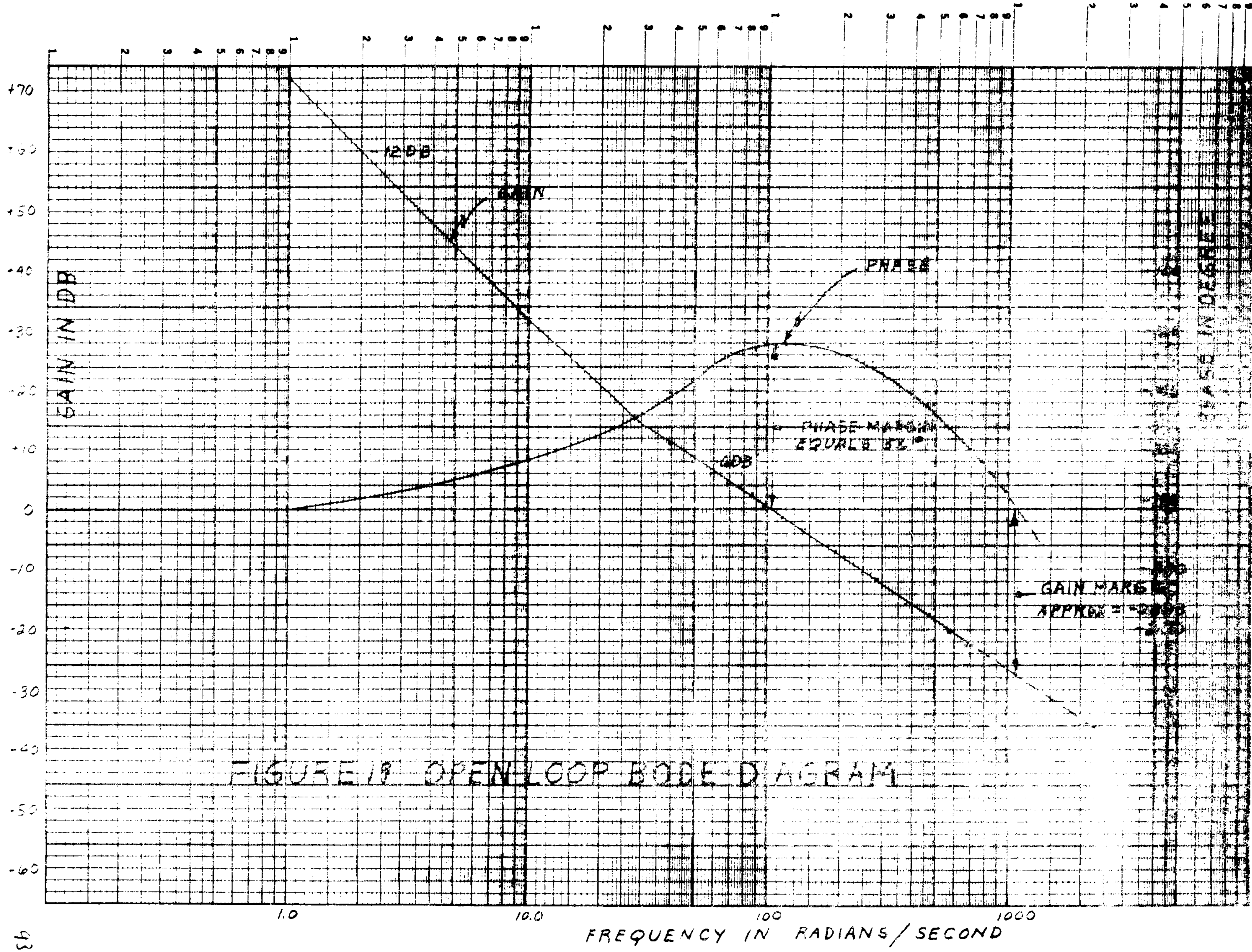


FIGURE 19 OPEN LOOP BODE DIAGRAM

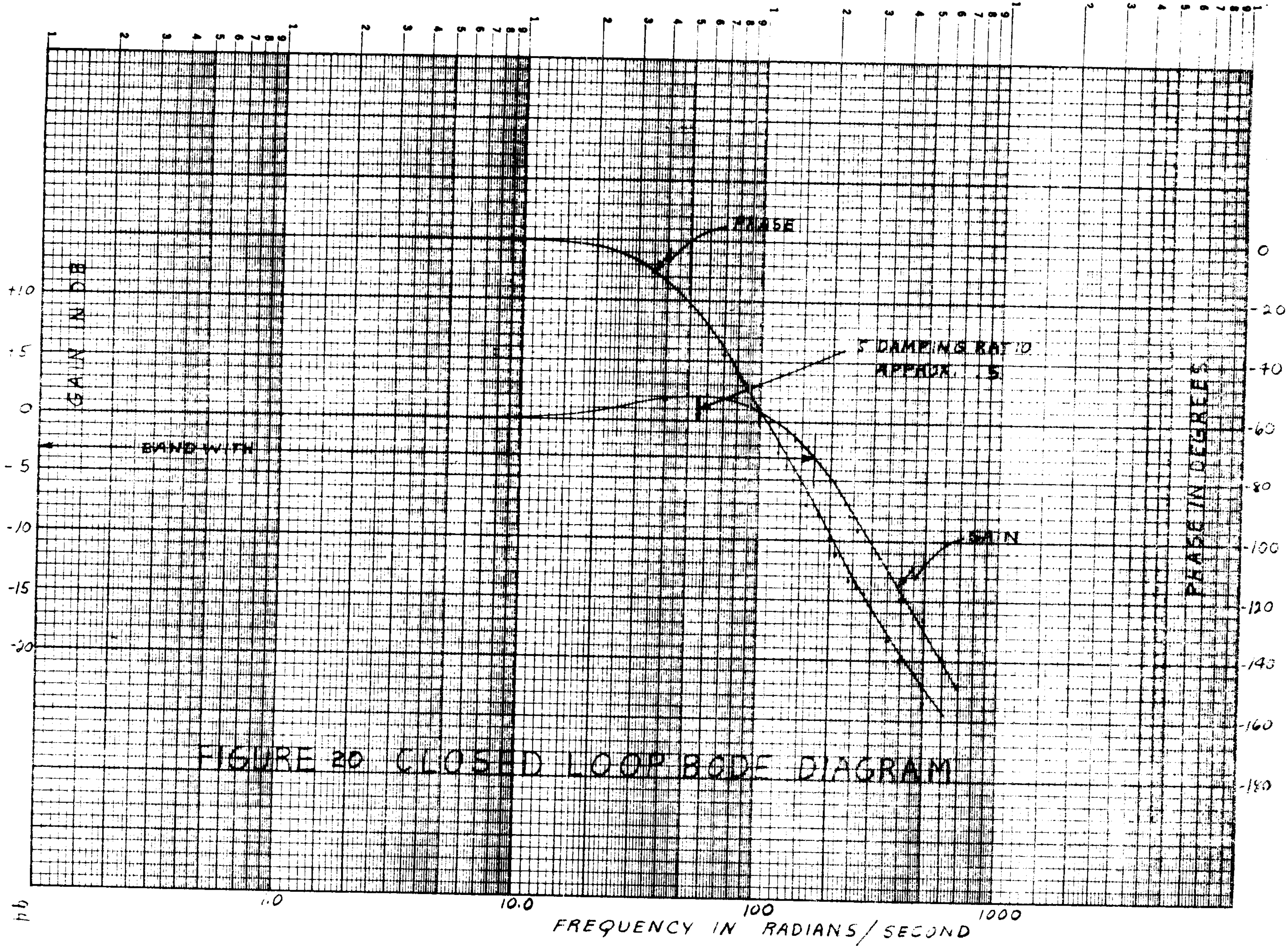


FIGURE 20 CLOSED LOOP BODE DIAGRAM

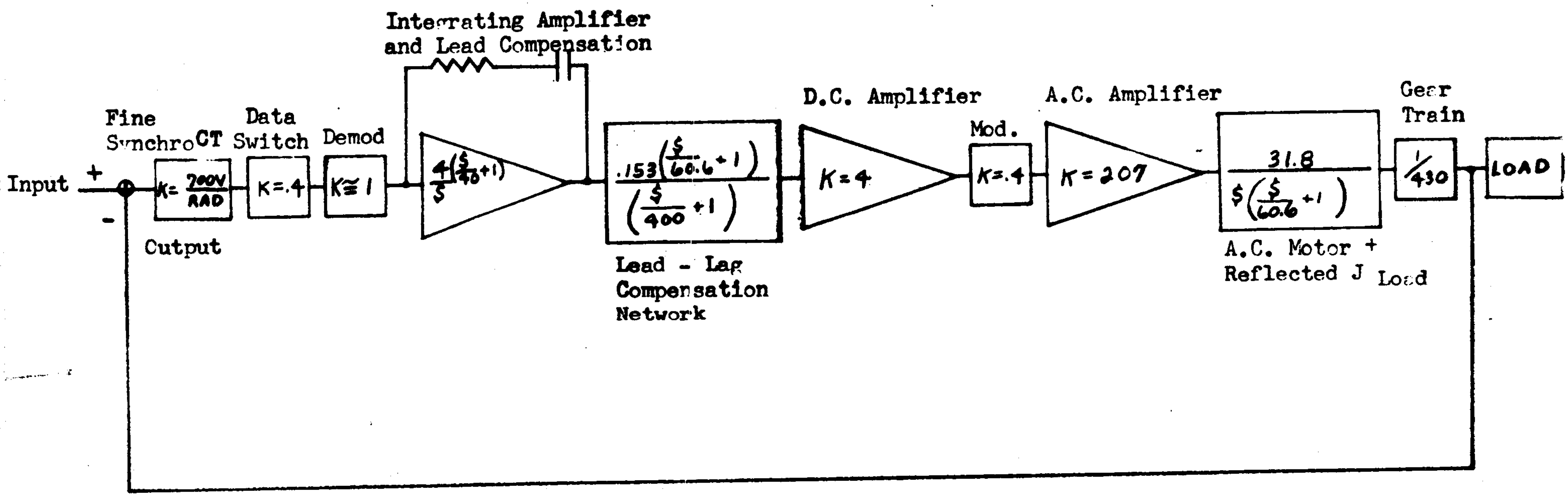
The damping ratio can be changed by varying the amplifier gain or by additional compensation.

d. Yaw Servo

The same procedure and steps were carried out on the anticipated yaw assembly of the optical pickup. The calculated moment of inertia based on the preliminary size and weights is 0.5 oz-in-sec^2. It is assumed that the compliance between the motor output shaft and the load can be made large enough to neglect structural effects. The block diagram is shown in Fig. 21 . The open loop, and closed loop diagrams are the same as those shown in Fig. 19 and Fig. 20 for the roll investigation. The only items that change are the gear train, the motor, the lead-lag compensation network, and the gain of the ac amplifier. The larger load inertia requires an increase in the gear train ratio to 430:1. This change in gear ratio calls for a motor with a higher no-load speed of 10,000 rpm. A Raystrom 8M4-H size 8 motor can be used. The transfer function of the motor plus the reflected inertia is $\dfrac{31.8}{S\left(\dfrac{S}{60.6}+1\right)}$.

The lead-lag compensation network transfer function changes to,

$\dfrac{.153\left(\dfrac{S}{60.6}+1\right)}{\left(\dfrac{S}{400}+1\right)}$. The ac amplifier gain would change from 207 v/v to 827 v/v; however, the change in gain of the lead-lag network calls for a dc amplification stage between the network and the modulator to increase the signal level at this point. The gain of this amplifier is 4 v/v and therefore changes the ac amplifier gain requirements from 827 v/v to 207 v/v.



NOTES: 1. Abbreviations

(a) CT - Control Transformer
(b) Demod. - Demodulator
(c) Mod. - Modulator
(d) J_{Load} - Load Moment of Inertia

FIGURE 21 - BLOCK DIAGRAM OF YAW SERVO

e. Pitch Servo

The pitch servo load is a very small prism whose inertia may be neglected. The loop will be basically the same as the roll servo loop with the exception of a change in the gear ratio and ac amplifier gain which is due to a change in maximum prism velocity from one radian per second to two radians per second.

For all practical purposes the compensation network could remain unchanged since the change in the inertial time constant of the motor armature and reflected load inertia would be very small.

The open and closed loop Bode diagrams would be the same as shown in Fig. 19 and Fig. 20 respectively.

f. Error Discussion

The total angular error that can be present in the servo systems discussed consists of two components, static errors and dynamic errors.

The static errors are caused by the manufacturing tolerances and friction present in the components which are used in the system. Some of these errors can be minimized but none can be completely eliminated. System alignment errors also fall into this category.

Dynamic errors will result in an angular misalignment between the reference and the command in the servo system whenever there is a change in the reference position, velocity, or acceleration. The magnitude of those errors depends on the type of servo system chosen. The type II system discussed above permits dynamic positional error to occur only during acceleration.

The static errors considered applicable are synchro manufacturing error, synchro gearing, synchro alignment, drift, noise, and friction.

In a size 8 synchro a manufacturing error of five, seven or ten minutes of arc can be expected. However, by selectivity this error can be reduced to three minutes. The three minutes can be reduced further by using a two-speed synchro system. A 31-to-1 gear ratio between the fine and coarse synchro reduces the error to $\frac{1}{31} \times 3$ or .097 minutes or approximately 0.1 minute. At least 0.5 of a minute can be expected in the synchro gearing even with anti-backlash gears and another 0.5 minute for synchro alignment. It is anticipated that drift, noise, and friction will contribute an additional 0.5 of a minute of arc.

The total error is based on the root sum square method. Therefore, the total error is equal to the square root of the sum of the squares of the static dynamic errors. The desired total error is 2 minute by definition. Thus maximum dynamic error allowable is about 1.65 minutes. This dynamic error along with the maximum acceleration is used to calculate the system K_a.

g. Conclusions

Based on the above discussion it appears theoretically feasible to design the pitch and yaw servo systems to meet the 2 minute accuracy goal. The effective roll servo accuracy will be about 2.8 minutes. The roll prism introduces a two-to-one increase in image rotation which increases the effect of the static servo system errors. However, the effective dynamic error can be maintained at 1.65 minutes.

5. TELEVISION SYSTEM DESIGN

a. General

The television equipment used in conjunction with the optical pickup device must be capable of providing a very high quality display in order to maximize utilization of the optical pickup capabilities. In addition to high performance it is desirable that the television equipment be of compact design and capable of reliable operation under dynamic conditions such as associated with a moving bridge assembly (camera) or cockpit motion system (display device).

The camera system could employ either a vidicon or an image orthicon to obtain the resolution given below (part b.) hence other system considerations must be used, including the availability of high resolution equipment, to determine which tube type to employ. The image orthicon (IO) is considerably more sensitive than the vidicon and has a lower lag characteristic. However, the signal to noise ratio is lower than that associated with a vidicon. The signal to noise ratio is determined by the image orthicon itself while external circuitry limits the vidicon. Also, the image orthicon is much larger than the vidicon and is somewhat limited in operating orientation hence requiring a larger mechanical design, higher power requirements and limited operating position. The vidicon image format is smaller, which is an advantage as far as the optical design is concerned. Equipment availability (See appendix H) indicates that industry has employed the vidicon tube more extensively in high quality television systems.

It is recommended, in light of the above, that a 1-1/2 inch vidicon camera be used. Better center to edge resolution can be obtained with a 1-1/2 inch vidicon and operating adjustments are less critical as compared to a one-inch vidicon. A television monitor is also recommended as a means of displaying the imagery since presently available monitors offer higher picture quality capabilities than current projection systems.

b. Minimum System Requirements

The television system should have the following minimum performance characteristics:

1. Vertical resolution of 800 television lines
2. Horizontal resolution of 1000 television lines center, 700 television lines corner. 4:3 aspect ratio
3. Ten shades of gray distinguishable
4. Vertical and horizontal scan linearity of ± 1 percent on axis.
5. Raster or geometric distortion of ± 2 percent.
6. Signal to noise ratio goal of 40 db.

The camera-control should include the following features:

1. High peaker circuit
2. Aperture correction
3. Automatic-or-manual target-control circuit
4. Keyed clamp circuit
5. Sweep protection
6. Variable gamma correction
7. Peak white clipper circuit

c. Special Considerations

In order to improve overall television system performance consideration should be given to the possibility of incorporating special circuitry such as vertical aperture correction (to improve vertical resolution) and lag reduction circuitry (to improve dynamic response).

Also the possibility exists for some image distortion correction to be incorporated into the television system. This correction would be performed by introducing nonlinearities into the sweep circuits. This type of correction would preferably be performed in the display device in order to minimize the effects on the display quality.
The magnitude of the distortion correction obtained by this means will necessarily be quite limited because of the electronic problems associated with the very high scanning rates.

SECTION V - FUTURE PROSPECTS

1. HOLOGRAPHY

Information-storage problems invariably have been a major consideration in simulation devices. Relief models in particular have offered the most straightforward means of data storage and retrieval in visual displays of large landmasses. This, in turn, has led to large models because of scale-factor considerations. Problems are further compounded by the requirements for servosystems, model illumination, support and drive structures, and space facilities to house the complete system equipment.

Recent technological advances have brought about means of storing three-dimension information in great detail on a single transparency. The process, called holography, employs physical optics technology and coherent light. The two dimensional transparency (hologram) is a recording of the frequency and phase relationships of light waves reflected from a three-dimensional object illuminated by a coherent source. Visually, the hologram itself is unintelligible data. A playback system similar to that which creates the hologram yields an aerial image in three dimensions.

This technique has three principal advantages:

1. The transparency size is not directly related to data stored; i.e., a small piece can be cut out of the hologram, and the complete scene still will be reproduced. This is because information from a point on the object is spread over the complete hologram. Conversely, each point on the hologram records data from every point of the illuminated object.

2. Resolution in the image is inherently high. The image does not suffer abberation problems encountered by optical systems.
3. It is possible to change the image size without appreciable loss of resolution.

Two approaches for implementing this technology are presently considered. An optical pickup device could be used without restrictions on simulated scaled altitude due to entrance pupil diameter. It also appears feasible to combine fss-transparency systems with holography to introduce three-dimensional data.

GAC is currently pursuing analytical and empirical studies of various coherent optical techniques to be used for visual-simulation data generation and processing. This work is being funded under an in-house development program and will employ a continuous-wave gas laser.

2. COMPONENTS

a. Television Pickup Tube Improvements

The Plumbicon and SEC vidicon appear to offer considerable developmental potential for improved television performance. The Plumbicon (vidicon type tube) has a very low lag characteristic and somewhat higher sensitivity than the vidicon. At the present time available one inch Plumbicons are limited to 700 - 800 TV lines of resolution. However, development of 1-1/2 inch or larger tubes would increase the resolution capabilities thus permitting its use in high resolution systems and the realization of the important advantages of increased sensitivity, and particularly the improved dynamic response due to the low lag characteristic. Development work is currently progressing toward this end.

The SEC vidicon also has a low lag characteristic as well as several hundred times the sensitivity of the vidicon; however, presently available tubes, which employ magnetic deflection and focusing, are limited in resolution to 700 - 800 TV lines and are physically large. An electrostatic laboratory version of the tube however, considerably reduces its physical size. Theoretical resolution capability of the SEC target is on the order of 2000 TV lines or better; hence it can be expected that much higher resolution will be attainable from future tubes. This improved tube would generate high resolution, low lag television displays with very low (compared to a vidicon) photocathode illumination. Both the SEC vidicon and the Plumbicon have good signal-to-noise ratios.

The focus projection and scanning (FPS) vidicons by GE reduce the physical size (shorter tube envelope) and operating power of pickup tubes while maintaining good resolution. Present tubes have a capability of 600 TV lines; however, future tubes will probably have increased resolution. Physically smaller high resolution TV cameras requiring less power could result from further application of this concept.

APPENDIX A - AREAS OF PRIMARY INVESTIGATION

A. Optics

1. <u>Wide Angle Optical Systems</u>

1.1 Refractive Systems

1.1.1 Wide Angle Objective Lenses (Field of View $\leq 120^{\circ}$)

1.1.2 Ultra-Wide Angle Objective Lenses (Field of View $> 120^{\circ}$)

1.1.3 Multiple Objective Lenses

1.2 Reflective Systems

1.3 Catadioptric Systems

2. <u>Depth of Field Problems</u>

2.1 Oblique Optics System

2.2 Multiple Pickup Tube System

B. Electronics

1. <u>Television Pickup Tubes</u>

2. <u>Other Techniques</u>

C. Integrated Systems

D. Systems Evaluation

1. <u>Depth of Field Limitations</u>

2. <u>Field of View Limitations</u>

3. <u>Six Degree of Freedom Limitations</u>

4. <u>Integrated System Performance</u>

APPENDIX B - TEXT OF SURVEY LETTER

Goodyear Aerospace Corporation (GAC) is currently conducting, for the National Aeronautics and Space Administration (NASA), Marshall Space Flight Center, a study of wide angle optical systems for use in visual simulations.

An initial task of this contract, NAS 8-11775, is to survey the present state of the art and impending developments. This is to be a two-part task consisting of: (1) queries to industry, research organizations and government agencies; and (2) visits to selected respondents' facilities for further information.

As an organization having interest in the field of visual simulation or related fields, your facility has been selected as a possible source of pertinent information. You are invited to submit information pertaining to concepts, designs, subsystems or components which may be directly applicable to:

1. Optically generated wide angle visual simulation imagery (from terrain or other models) having infinite depth of field for all situations down to extremely small object distances.
2. Imagery generated from other than three dimensional terrain model storage, having either or both of the specific qualities (large angular field and infinite depth of field) cited in (1).

APPENDIX C - SURVEY LETTER RECIPIENTS

No.	Name	Locations
1.	Aeronautical Chart & Information Center	St. Louis, Missouri*
2.	Aero Service Corporation	Philadelphia, Penna.*
3.	Aerospace Corporation	Los Angeles, Calif.*
4.	American Car and Foundry	Riverdale, Md.*
5.	American Optical Company	Pittsburgh, Pa.
6.	ASD, Wright Patterson AFB	Dayton, Ohio
7.	Austin Company	New York, N.Y.
8.	Bausch & Lomb	Rochester, N.Y.
9.	Bell Aerosystems	Buffalo, N.Y.
10.	Boeing Company	Wichita, Kansas* Seattle, Washington
11.	Celco-Constantine Engrg. Labs	Mahwah, New Jersey
12.	Dage Electric Co., Inc.	Franklin, Indiana
13.	Dalto Electronics Corp.	Norwood, New Jersey*
14.	Dumont Laboratories	Clifton, New Jersey
15.	Eastman Kodak	Rochester, N.Y.*
16.	Eidophor-CIBA-Pharmaceutical Products Inc.	Summit, New Jersey
17.	Elgeet Optical Co., Inc.	Rochester, N.Y.*
18.	Engineering & Research Corp.	Riverdale, Md.
19.	Farrand Optical Co.	New York, N.Y.*
20.	Ferson Optics	Ocean Springs, Miss.*
21.	General Dynamics/Astronautics /Electronics	San Diego, Calif. San Diego, Calif. Fort Worth, Texas Groton, Conn.*
22.	General Electric Company	Syracuse, New York Utica, New York Decatur, Illinois
23.	General Precision Inc.	Little Falls, N.J. Morton Grove, Ill.
24.	Grumman Aircraft Corporation	Bethpage, L.I., N.Y.
25.	Hughes Aircraft Co.	Fullerton, Calif.*
26.	IBM Space Center	Owego, New York*
27.	Institute of Optics	Rochester, New York

* Reply Received

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No.	Name	Locations
28.	Ling-Temco-Vought	Dallas, Texas
29.	Link - Division General Precision, Inc.	Binghamton, N.Y.
30.	Litton Industries	San Carlos, Calif.
31.	Marquardt Corporation Pomona Division	Pomona, Calif.*
32.	McDonnell Aircraft Corporation	St. Louis, Mo.
33.	Melpar Incorporated	Falls, Church, Va.
34.	MGD-Research & Development Corp.	Englewood Cliffs, N.J.*
35.	Motorola Incorporated	Chicago, Illinois Scottsdale, Arizona
36.	NASA-Manned Spacecraft Center	Houston, Texas
37.	Nat'l. Scientific Laboratory Inc.	Washington, D.C.*
38.	North American Aviation	Los Angeles, Calif. Downey, California*
39.	Pacific Optical Co.	Inglewood, Calif.*
40.	Perkin-Elmer	Norwalk, Connecticut
41.	Philco Corporation	Lansdale, Pa. Palo Alto, Calif.
42.	Radio Corporation of America	Camden, N.J. Harrison, N.J. Princeton, N.J.
43.	Reflectone	Stamford, Conn.
44.	Research & Technology Div. Air Force Systems Command	Dayton, Ohio
45.	Rheem Manufacturing Company Defense Prod. Division	Downey, California
46.	Scanoptic Incorporated	Woodside, New York*
47.	Sylvania Electronics Corp.	Buffalo, N.Y.* Emporium, Penna.* Seneca Falls, N.Y.
48.	Tropel Incorporated	Fairport, New York
49.	University of Illinois	Urbana, Illinois
50.	US Naval Training Devices Center	Port Washington, N.Y.*
51.	H. A. Wagner Company	Van Nuys, Calif.
52.	Westinghouse Electric Corp.	Pittsburgh, Pa.

* Reply Received

77-10 (5-63) REF: ENGINEERING PROCEDURE S-017

APPENDIX D - COMPUTER AND IN-HOUSE SEARCH LITERATURE

1. Physical and Technical Problems in the Development of TV Camera Tubes, NASA Document No. N64-31330, September 1964.
2. Feasibility for Research Application of Visual Attachments for Dynamic Flight Simulators, Report No. 1 State-of-the-Art-Survey of the Visual Simulation Industry, Human Sciences Research Incorporated Report No. HR-RR-62/7-Mk-X, July 1962.
3. Space Flight Visual Simulation Systems, Volume 16, Part 2 of Advances in Astronautical Sciences, The American Astronautical Society, September 1963.
4. Feasibility Study Wide Angle Television Display, General Electric Report No. R56-ELS-74, November 1956.
5. Final Report, Design Study, UFS-2, NASA Document No. N63-15804, September 1962.
6. Basic Development Accomplished on Wide-Angle Non-Programmed Visual Presentations, Volume I, Technical Report NAVTRADEVCEN 404, April 1959.
7. Basic Development Accomplished on Wide-Angle Non-Programmed Visual Presentations, Volume II, Technical Report NAVTRADEVCEN 404, April 1959.
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10. AIAA/NASA Third Manned Space Flight Meeting, AIAA Publications No. CP-10, November 1964.
11. Pilot's Control of Lifting Body Simulation, Aviation Week and Space Technology, 4 May 1964.

12. Langley Simulators Perform Visual Tasks, Aviation Week and Space Technology, 13 April 1964.

13. All-Weather TV Display Adds Realism to Simulated Landings, Control Engineering, February 1963.

14. Minimizing The Effects of Vidicon Lag with a Long Video Delay Line, IRE Transactions on Broadcasting, Vol. PGBC - 7 August 1961.

15. Secondary Electron Conduction (SEC) For Signal Amplification and Storage in Camera Tubes, Proceedings of the IEEE, September 1964.

16. The Plumbicon, A New Television Camera Tube, Philips Technical Review, Volume 25, 1963/64.

17. Development of Visual Simulation Techniques for Astronautical Flight Training Vol. I, Tech. Documentary Report No. AMRL-TDR-63-54.

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19. A Survey of Simulators used as Tools for Research, Design and Development, Aerospace Information Report AIR779, 20 June 1964.

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21. Boeing Space Flight Simulator, Brochure

22. Low-Altitude, High-Speed Visual Acquisition of Tactical and Strategic Ground Targets - Part 1, D6-2385-1, August 1964.

23. Langley Research Center Simulation Facilities for Manned Space Missions, April 1963.

24. Discussion of Existing and Planned Simulators for Space Research, August 1964.

25. Simulation Environment, Tech. Facilities Manual, Volume III, NAFEC, April 1965.

26. GPS Visual Flight Attachments for Flight Simulators, General Spec SD/440/S Issue 1, October 1964.

27. Theory and Operation of Step-Servo Motors, EDN Design Data, July 1963.

28. AC & DC Servomotors, Systems Designer Handbook, January 1965.

29. Final Report, Automobile Simulator Feasibility Study. Cornell Aeronautical Laboratory, Buffalo, N.Y., November 1958.

APPENDIX E - RELATED PATENTS

3,033,082 (U.S.), Inverted Telephoto Objectives, May 1962

3,039,360 (U.S.), Lens With Remote Entrance Pupil, June 1962

3,030,857 (U.S.), Image Rotating Optical System, April 1962

2,947,219 (U.S.), Wide Angle Objective Lens, August 1960

2,579,177 (U.S.), Optical Projection Apparatus, December 1951

2,979,832 (U.S.), Visual Simulator For Flight Training Device, April 1961

2,591,752 (U.S.), Flight Trainer, April 1952

3,076,271 (U.S.), Flight Training and Evaluating Equipment, February 1963

3,052,753 (U.S.), Image Projection Apparatus, September 1962

3,071,875 (U.S.), Method and Means For Correcting Parallax

3,015,988 (U.S.), Perspective Alteration Means, January 1962

APPENDIX F - PRELIMINARY SPECIFICATION, ADVANCED OPTICAL PICKUP SYSTEMS

1. SCOPE

1.1 This document defines requirements for a family of unprogrammed real time visual simulation optical pickup systems which will provide imagery of extreme field and depth of field at minimum working distances.

2. PURPOSE

2.1 These optical pickup systems shall be movable under computer control relative to an object surface in such a manner as to provide a continuous view which will be analogous to that seen from a spacecraft or aircraft undergoing six-degree-of-freedom maneuvers.

3. REQUIREMENTS

3.1 Components - The optical pickup shall consist of the following major components:

Item	Nomenclature	Reference Paragraph
1	Objective Lens System	3.5.1
2	Compensation System	3.5.2
3	Angular Motion System	3.5.3
4	Interface & Control System	3.5.4

3.2 Selection of specifications and standards - specification and standards shall be selected in accordance with good government and commercial practice as reflected in comparable systems of recent manufacture. Final selection shall be based upon review by the procuring agency of contractor preliminary detail design layouts and supporting technical data.

3.3 A major objective shall be the attainment of a design which provides self-compensation and inherent automation so as to permit the maximum degree of utilization with existing visual simulation system designs. These inherent qualities shall be such as to minimize the need for additional computation or special signal processing, exterior to the optical pickup/visual system interface.

3.3.1 Design of the pickup shall be such that overall size and weight shall be kept to a minimum compatible with functional requirements.

3.3.2 Visual interface - The pickup shall terminate in an adapter assembly which shall permit attachment to the majority of comparable visual simulator translational systems by a minimum of modification to the latter.

3.3.3. Covers - Dust and safety covers shall be provided for mechanical gear assemblies where dust or other foreign matter would degrade the operation of the system.

3.3.4 Calibration and alignment - The following calibration and alignment provisions shall be incorporated in the system design.

a. Means to accurately establish known input conditions (command signals) to the system.

b. Means to establish and verify the physical location of the system entrance pupil or look point relative to a viewed surface, and the pointing direction (in three-dimensional space) of the system optical axis in terms of visually-indicated angular motion axes settings.

c. Means to accurately pre-set, by mechanical and/or electrical control, any desired optical-axis pointing direction.

3.3.5 Interlocks - Protective interlocks with an override capability shall be provided on the angular motion system. Provision shall be made to transmit a signal to the altitude motion system of a visual simulator with which the optical pickup is used, in order to freeze or reverse vertical motion in case of impending hazard to the pickup or viewed surface.

3.3.6 Human factors requirements - The following human factors requirements shall be incorporated into the design.

3.3.6.1 Safety provisions - The system shall provide maximum protection from electrical and mechanical hazards to operating and maintenance personnel.

3.3.6.2 Maintenance - The system shall be designed to permit ready access to all functional subassemblies for maintenance and calibration purposes.

3.3.7 Drawings - The contractor shall provide preliminary functional schematics and layout drawings for approval of the procuring agency prior to manufacture of the hardware. Final drawings shall be submitted at the time of formal acceptance.

3.4 Performance - The optical pickup shall operate as specified herein throughout ambient room temperatures ranging from +16° to +38°C. This may be accomplished either by maintaining component performance through the temperature range or by proper air conditioning of the units. The optical pickup shall withstand temperatures, while nonoperable, of -40° to +55°C for long periods of time without sustaining permanent damage to components.

3.5 Component description - Optical pickup system components shall function in the manners and with the accuracies and tolerances specified in the following paragraphs.

3.5.1 Objective lens system - An objective lens system shall be used which shall provide a constant field of view of 100 or more degrees. The lens system shall consist of existing or special multi-element designs.

3.5.1.1 Entrance pupil - The location of the objective lens system entrance pupil shall be optimized to permit minimum working distances in relation to the viewed surface.

3.5.1.2 Aperture ratio - The objective lens system shall be designed to operate in conjunction with the rest of the optical pickup such that resulting aperture ratios (f/nos.) shall be at all times optimized in terms of depth of field and television pickup tube illumination requirements. Minimum aperture ratios shall be no larger than f/10.

3.5.1.3 Resolution - Resolution shall be maximized to obtain the least possible degrading effect on the performance of any visual simulation system with which the optical pickup may be used.

3.5.2 Compensation system - A compensation system shall be provided which shall, through the use of electrically controlled mechanical linkages, minimize the effects on the final system imagery of all distortions, aberrations and other fixed and variable phenomena inherent in the selected objective lens system design.

3.5.2.1 Final imagery - The final imagery shall be a scaled analog of imagery which would be generated by a rectalinearly-propagating optical system having the performance specified in paragraph 3.5.1. The imagery shall be such as to be readily focusable on the photocathode of a closed circuit television camera pickup tube for transformation and routing to an electronic display system which is capable of reconstructing the perspective geometry of the objective lens system field of view.

3.5.2.1.1 Masking - Means shall be provided to effectively vary the format of the final imagery to accommodate various aspect ratios used or desired in existing visual simulation systems. Format changes shall be accomplished in a simple, direct manner as by replacement of masking apertures.

3.5.2.1.2 Format size - Format size of the final imagery shall be fixed. The contractor shall recommend a format size in keeping with the current state of the television camera pickup tube art and with consideration for the tube sizes in current use in existing visual simulation systems. The contractor shall investigate the feasibility of providing an optical pickup design which will provide readily changeable format sizes.

3.5.2.2 Aperture effects - The effects of the aperture on image illumination shall be optimized through the operating range of the pickup. Aperture size shall be closely controlled to assure maximum depth of field while maintaining adequate light levels at the final imagery plane.

3.5.2.3 Distortion - Optical means shall be employed to remove distortions due to the type of objective lens used, and also those resulting from any special methods of pickup system optimization, including both optical and mechanical performance considerations.

3.5.3 Angular motion system - The angular motion system shall recreate the variations in geometric perspective of the pilot or observer due to vehicle attitude changes. The angular motion system shall operate in conjunction with the rest of the optical pickup to permit wide variations in the position of the lookpoint relative to the simulated vehicle center of gravity.

3.5.3.1 Motion servos - The three vehicle attitude motions shall be computer commanded via servo-controlled mechanical linkages. The servos shall be high precision types which will provide the following performance as a design objective:

a.	Maximum acceleration	2 radians/sec^2
b.	Maximum velocity	2 radians/sec
c.	Displacement	Continuous
d.	Positional tracking accuracy	2-3 minutes of arc

3.5.3.2 System pointing accuracy - Angular motion system pointing accuracy shall be better than five minutes of arc as a design objective.

3.5.3.3 Lookpoint stability - The entrance pupil location shall represent the lookpoint of the simulated vehicle occupant and shall be maintained at a point in space which shall not vary by any detectable amount as a result of optical pickup system angular motion. The criterion for detectability shall be the presence or absence of apparent changes in simulated altitude or slant ranges resulting solely from pickup angular motion system operation. This criterion shall be tested by examination of a geometrically-correct display of selected object information viewed by the optical pickup. The optical pickup shall be tested in the absence of translational motion. The contractor shall perform a preliminary analysis to determine acceptable quantitative values of lookpoint variation, and define methods for accurately measuring the performance of the delivered system.

3.5.4 Interface and control system - The interface and control system shall operate in conjunction with the rest of the optical pickup to accept computer or locally-generated command signals.

3.5.4.1 Local control - An optical pickup control panel shall be provided with slewing switches which shall be usable for locking out computer-generated command information and re-positioning the attitude motion axes for calibration and maintenance purposes. Slewing rates shall be pre-set to provide two effective rotational velocities. A coarse rate shall provide rapid motion. A fine rate shall permit very precise alignment to achieve any desired optical axis pointing direction. The panel shall be locatable up to 10 feet from the pickup.

3.5.4.2 Readout - A display shall be provided to indicate precise instantaneous coordinate values on each of the three angular motion system axes.

3.5.4.3 Separate operation - Appropriate power supplies, interlocks and controls shall be provided to permit operation of the optical pickup system in complete isolation from the other portions of a visual simulation system.

3.5.4.4 Racks and cabinets - Standard electronic racks and cabinets shall be provided to house power supplies, servo amplifiers and related equipment in a location up to 10 feet from the optical pickup.

3.5.5 Radio frequency interference - Filter networks, shielding and other required means shall be employed to minimize the propagation of system-generated radio frequency interference to adjacent sensitive electronic equipment such as television, servomechanism or calibration and maintenance test equipment.

3.5.6 Crew compartment motion compatibility kit - The compatibility kit for simulators with cockpit motion shall include components and circuitry necessary to compute difference bank and difference pitch angles as camera or optics inputs. These difference angles shall be equal to the simulator computed angles minus the actual cockpit motion angles.

4. QUALITY ASSURANCE

4.1 Responsibility - The contractor is responsible for the performance of all inspection requirements as specified herein. The contractor may utilize his own or any other inspection facilities and services acceptable to the procuring agency. Inspection records of the examination and tests shall be kept complete and available as specified in the contract or order.

4.2 Classification of tests - The inspection and testing of the optical pickup shall consist of acceptance tests.

4.3 Test conditions - The acceptance tests shall be conducted under operational atmospheric conditions as specified in paragraph 3.4

4.4 Acceptance tests - Each optical pickup shall be subjected to the following:

a. Visual examination of product
b. Optical, electrical and mechanical performance

4.5 Contractor-prepared test outline - The contractor shall prepare a test outline which shall define detailed procedures whereby the compliance of the delivered optical pickup with the requirements of this specification may be quantitatively and qualitatively verified.

5. PREPARATION FOR DELIVERY

5.1 Preservation and packaging - The contractor shall submit to the procuring agency for approval a detailed plan for preservation and packaging of the complete optical pickup system. It is recommended that this shall include layout sketches of a special container for the optical pickup assembly proper.

APPENDIX G - OBLIQUE OPTICS, MATHEMATICAL DESCRIPTION

The following is a general mathematical description of oblique optics based on first order theory. The following is a list of the parameters involved, together with their description. The coordinate system has been chosen so that the x axis is co-linear with the optical axis, and the y axis perpendicular to it at the entrance pupil of the lens. (Refer to Figure 1 .)

h = height of lens above object plane

γ = depression angle of optical axis

δ = instantaneous look angle

τ = angle between inclined image plane and optical axis

f = focal length of lens

R_s = slant range

R_g = ground range

s = object distance for which lens is sharply focused

m = magnification = image distance/object distance = image height/object height

Basic Geometry

The lines extended from the image plane, object plane and nodal plane of the lens intersect at a common point for a finite set of conjugates as shown in Figure 1 . The following proof of this statement - although not unique to this program - is presented here for the sake of completeness.

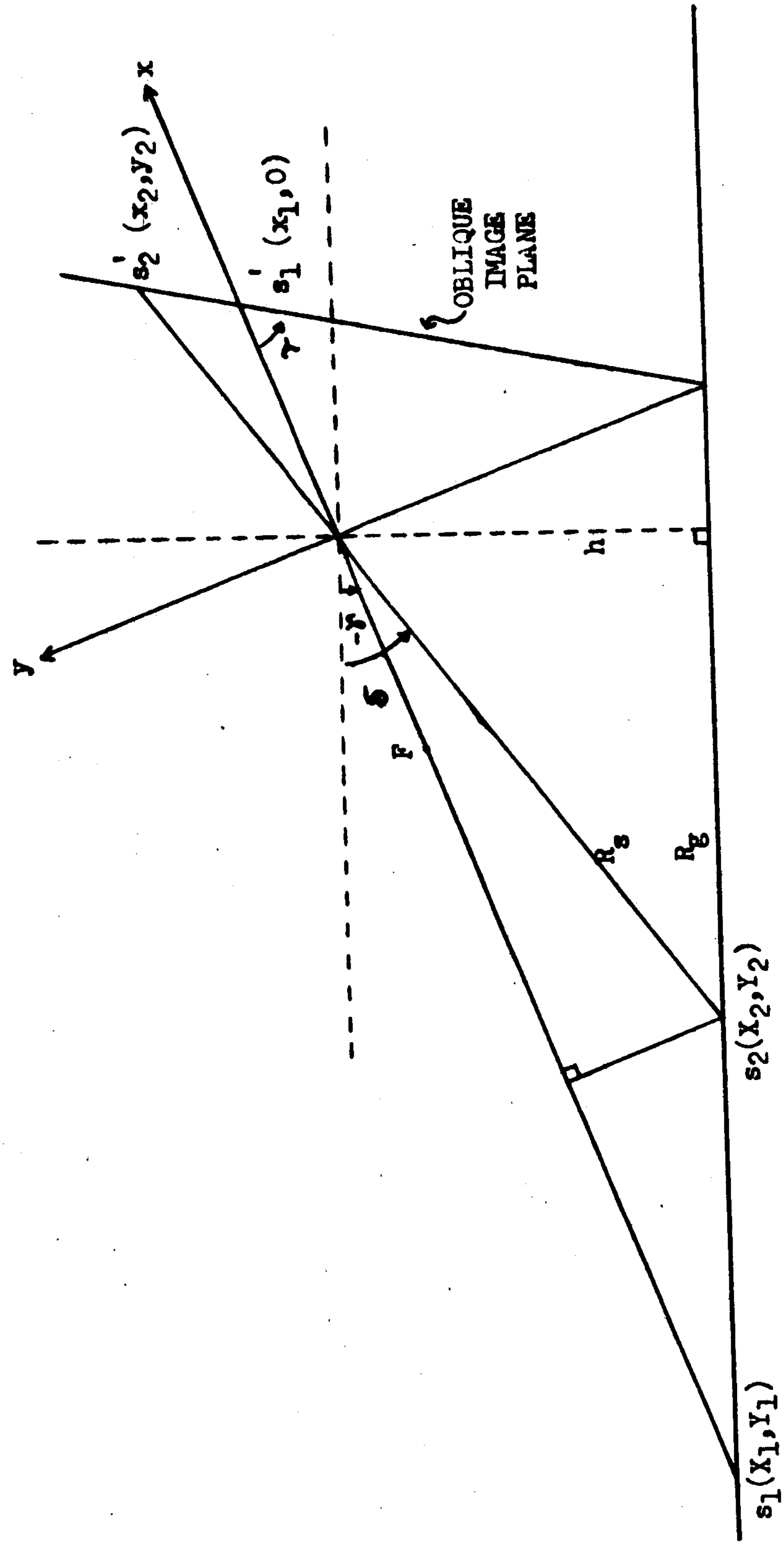


FIGURE 1 - MATHEMATICAL MODEL

The point s_1' on the image plane is given by:

$$\frac{1}{F} = \frac{1}{X_1} + \frac{1}{x_1}$$

$$x_1 = \frac{X_1 F}{X_1 - F} \tag{1}$$

$$y_1 = mY_1 = \frac{x_1}{X_1} Y_1 = 0 \tag{2}$$

The point s_2' on the image plane is similarly found.

$$x_2 = \frac{X_2 F}{X_2 - F} \tag{3}$$

$$y_2 = \frac{x_2}{X_2} Y_2 = \frac{FY_2}{X_2 - F} \tag{4}$$

The equation of the line formed by $s_1\ s_2$ is found from:

$$\frac{x - x_1}{x_2 - x_1} = \frac{y - y_1}{y_2 - y_1} \tag{5}$$

In the coordinate system being used (see figure 1),

$x_1 = -X_1$, $x_2 = -X_2$, $y_1 = 0$, and $y_2 = -Y_2$.

Then:

$$\frac{x + X_1}{X_1 - X_2} = \frac{y}{-Y_2}$$

$$y = \frac{-Y_2(x + X_1)}{X_1 - X_2} \tag{6}$$

At the y intercept,

$$y = \frac{-X_1 Y_2}{X_1 - X_2} \tag{7}$$

Likewise, the equation of the line formed by s'_1, s'_2 is found from equation (5) with the x and y values given in equations (1) through (4).

$$\frac{x = \dfrac{X_1F}{X_1-F}}{\dfrac{X_2F}{X_2-F} - \dfrac{X_1F}{X_1-F}} = \frac{y(X_2-F)}{FY_2}$$

$$\frac{\dfrac{X(X_1-F) - X_1F}{X_1-F}}{\dfrac{X_1X_2F - X_2F^2 - X_1X_2F + X_1F^2}{X_1X_2 - X_1F - X_2F + F^2}} = \frac{y(X_2-F)}{FY_2}$$

$$\frac{x(X_1-F)-X_1F}{X_1-F} \cdot \frac{X_1X_2-X_1F-X_2F+F^2}{F^2(X_1-X_2)} = \frac{y(X_2-F)}{FY_2}$$

$$y = \frac{xY_2F(X_1-F)\,[X_1X_2-X_1F-X_2F+F^2] - X_1Y_2F^2\,[X_1X_2-X_1F-X_2F+F^2]}{F^2(X_1-X_2)(X_1X_2-X_1F-X_2F+F^2)}$$

$$y = \frac{xY_2(X_1-F)-X_1Y_2F}{F(X_1-X_2)} \qquad (8)$$

At the y intercept, x = 0 and

$$y = \frac{-X_1Y_2}{(X_1-X_2)} \qquad (9)$$

Equations (9) and (7) equal and $s(0,Y) = s'(0,Y)$ and the line $s'_1s'_2$ intersects the y axis at the same point as does the line s_1s_2.

Location of Image Plane

The general equation of a straight line can be expressed as:

$$y = mx + b,$$

and from equation (8),

$$m = \frac{Y_2(X_1-F)}{F(X_1-X_2)} \quad \text{and} \quad b = \frac{-X_1Y_2}{(X_1-X_2)} .$$

Now from Figure 1 ,

$$\frac{Y_2}{(X_1 - X_2)} = \tan\gamma$$

$$\frac{h}{X_1} = \sin\gamma \; ; \quad X_1 = \frac{h}{\sin\gamma}$$

Then:

$$m = \frac{1}{F} \tan\gamma \left(\frac{h}{\sin\gamma} - F \right)$$

$$m = \frac{1}{F} \frac{\sin\gamma}{\cos\gamma} \left(\frac{h - F\sin\gamma}{\sin\gamma} \right)$$

$$m = \left(\frac{h - F\sin\gamma}{F\cos\gamma} \right) \tag{10}$$

and

$$b = -\frac{h}{\sin\gamma} \tan\gamma$$

$$b = -\frac{h}{\cos\gamma} \tag{11}$$

Then Eq. (8) becomes, in the x-y coordinate system,

$$y = x\left(\frac{h-F\ \sin\gamma}{F\ \cos\gamma}\right) - \frac{h}{\cos\gamma} . \tag{12}$$

The equation of the image plane in the

y'x' system may be found from

$$\begin{aligned} x' &= x\cos\xi + y\sin\xi \\ y' &= y\cos\xi - x\sin\xi \end{aligned} \tag{13}$$

Now

$$\xi = -\gamma \quad \text{and} \quad \sin(-\gamma) = -\sin\gamma$$
$$\cos(-\gamma) = \cos\gamma$$

Then (13) becomes

$$\begin{aligned} x' &= x\cos\gamma - y\sin\gamma \\ y' &= y\cos\gamma + x\sin\gamma \end{aligned} \tag{14}$$

At s'_1, $y = 0$ and from (12), $x_1 = \dfrac{hF}{h-F\sin\gamma}$, so

$$\begin{aligned} x'_1 &= \frac{hF\ \cos\gamma}{h-F\ \sin\gamma} \\ y'_1 &= \frac{hF\ \sin\gamma}{h-F\ \sin\gamma} \end{aligned} \tag{15}$$

At s'_2, $x = 0$ and from (12) $y = -\dfrac{h}{\cos\gamma}$, and

$$\begin{aligned} x'_2 &= h\tan\gamma \\ y'_2 &= -h \end{aligned} \tag{16}$$

Using (5), the equation of a line,

$$\frac{x' - \dfrac{hF\cos\gamma}{h-F\sin\gamma}}{h\tan\gamma - \dfrac{hF\cos\gamma}{h-F\sin\gamma}} = \frac{y' - \dfrac{hF\sin\gamma}{h-F\sin\gamma}}{-h - \dfrac{hF\sin\gamma}{h-F\sin\gamma}}$$

$$y' = x'\left(\frac{h\cos\gamma}{F-h\sin\gamma}\right) - \frac{hF}{F-h\sin\gamma} \qquad (17)$$

<u>Image Plane Orientation</u>

The angle at which the oblique image plane intersects the x-axis (optical axis of lens) is defined as τ

$$\tan\tau = \frac{Y}{s'_1}$$

Now

$$s'_1 = \frac{s_1 F}{s_1 - F}$$

$$Y = \frac{h}{\cos\gamma}$$

and

$$\tan\tau = \frac{h(s_1 - F)}{s_1 F\cos\gamma}$$

$$s_1 = h/\sin\gamma$$

$$\tan\tau = \frac{h - F\sin\gamma}{F\cos\gamma} \qquad (18)$$

It should be noted that the plane of zero distortion is 90° to the optical axis so that $\tan \tau = \infty$. This occurs if $\gamma = 90^{\circ}$, which is expected. It should also be noted that $\tan \tau$ is large if h is greater than F or if γ is large. Eq. (18) can be normalized by defining $\frac{h}{F} = Q$. Then

$$\tan \tau = \frac{Q - \sin \gamma}{\cos \gamma} \tag{19}$$

Figure 2 is a graph of τ vs γ for particular Q values. If τ is to be large ($\frac{\pi}{3} \le \tau \le \frac{\pi}{2}$) then $h \ge 2F$.

Distortion

Where longitudinal magnification is not equal to unity, distortion is inherent in the inclined image plane concept. That is, the image of the model surface focused on the inclined image plane does not meet the standard definition of a distortionless image. The following is an analysis of this distortion.

Define R as the ratio of x (axial distance from lens to any intersection point on the image plane) to x_o (the distance from the lens to the point at which the image plane crosses the x axis). The point x_o determines the location along the x axis at which the plane of zero distortion is located.

From Eq. (12):

$$y = x \left(\frac{h - F \sin \gamma}{F \cos \gamma}\right) - \frac{h}{\cos \gamma}$$

$$y = x \tan \omega$$

$$x\left(\tan \omega - \frac{h + F \sin \gamma}{F \cos \gamma}\right) = -\frac{h}{\cos \gamma}$$

$$x = \frac{h\,F}{h - F \sin \gamma - F \cos \gamma \tan \omega}$$

$$x_o = \frac{h\,F}{h - F \sin \gamma}$$

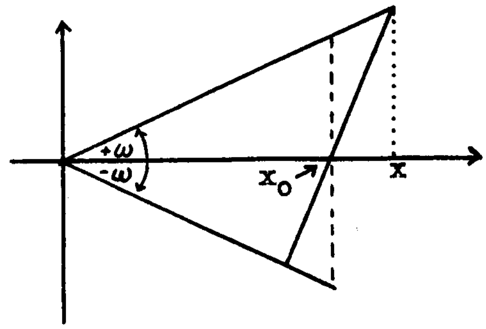


Figure 3

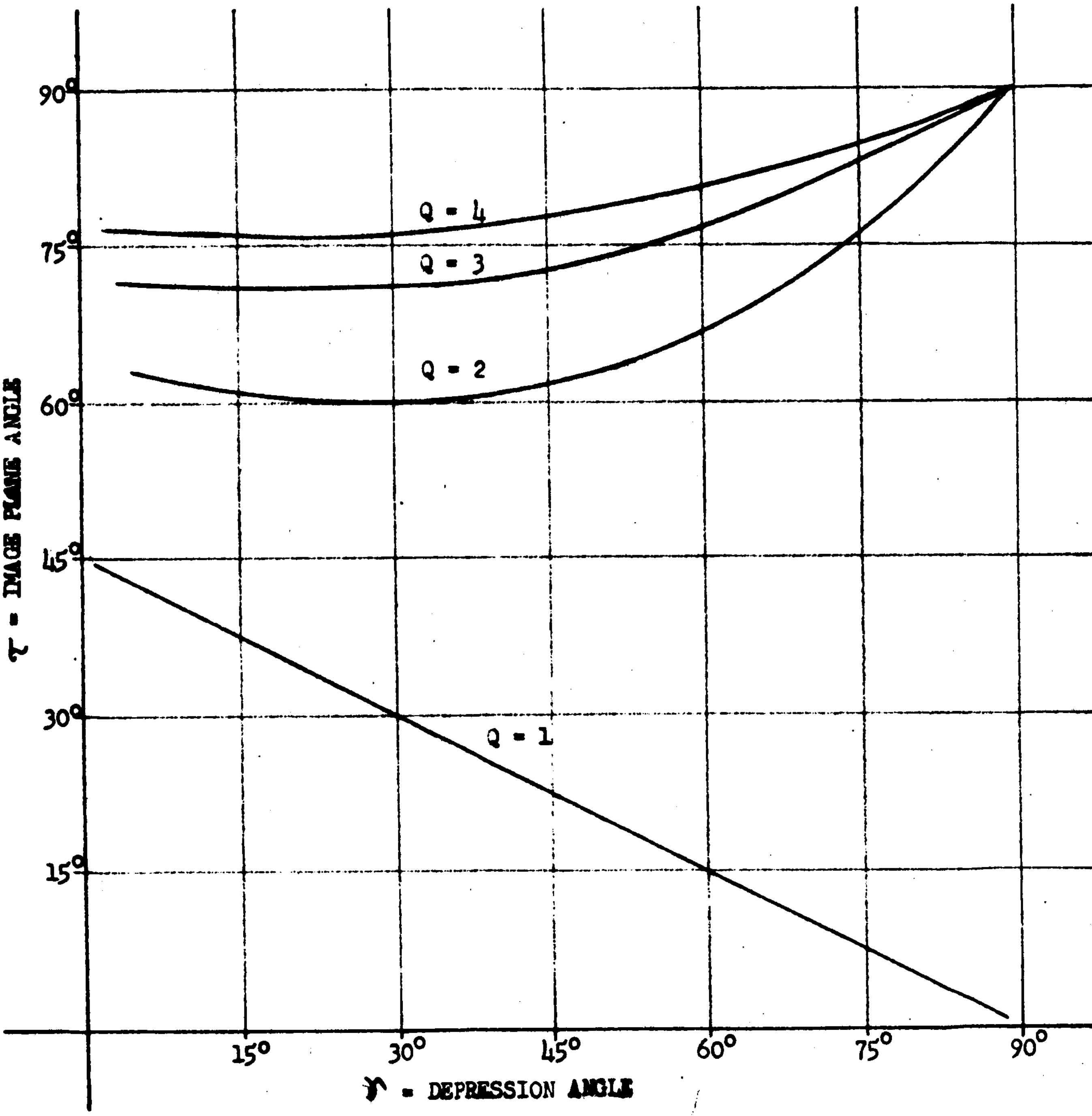


FIGURE 2: γ VS τ

$$R = \frac{x}{x_o} = \frac{h - F \sin}{h-F \sin\gamma - F \cos\gamma \tan\omega} \tag{20}$$

Since $0 < R < \infty$ must hold for a real image, h has an upper bound of $h > F \sin\gamma + F \cos\gamma \tan\omega$ and a lower bound of $h > F \sin\gamma$.

Equation (20) may be simplified by expressing h in terms of F. Let $h = Q F$. Then,

$$R = \frac{Q - \sin\gamma}{Q-\sin\gamma - \cos\gamma \tan\omega} \tag{21}$$

The boundry conditions become

$Q > \sin\gamma$ (for $-\omega$)

and

$Q > \sin\gamma + \cos\gamma \tan\omega$ (for $+\omega$)

Figure 4 shows the plot of Q vs γ for particular values of ω . The curves define the minimum value of Q for given values of γ and ω for which $\dot{R} = \infty$. Q must be greater than Q_{min} in order to have a correctable system.

3.2 Percent Distortion

The magnitude of the perspective distortion is best presented in terms of %. Define $\% \Delta m$ as the percent of distortion. Then,

$$\% \Delta m = \frac{x_o - x}{x_o} \times 100 \tag{22}$$

From Eq. (12) and Figure 3 ,

$$y = x \left(\frac{h - F \sin\gamma}{F \cos\gamma} \right) - \frac{h}{\cos\gamma}$$

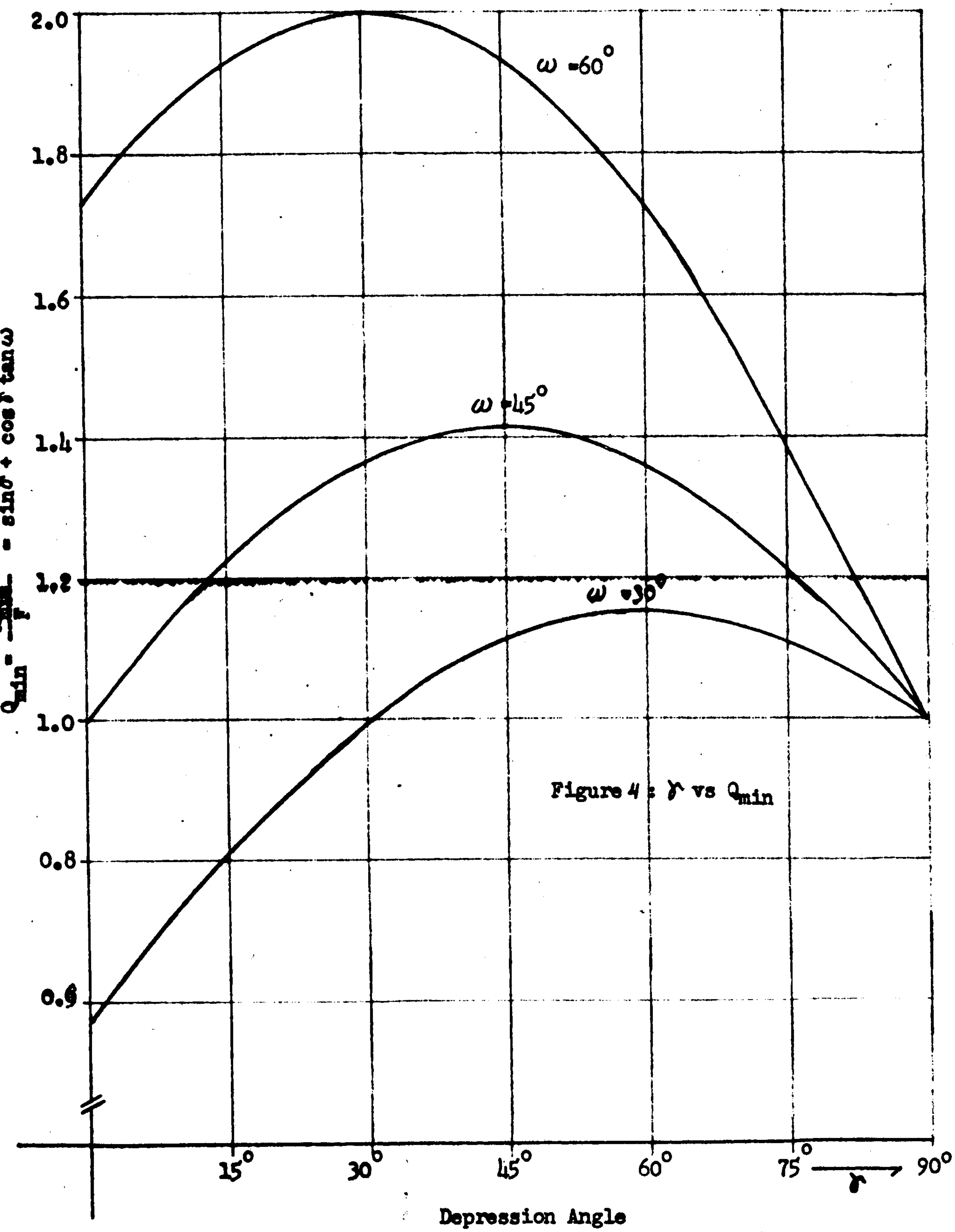


Figure 4 : γ vs Q_{min}

$$y = x \tan\omega$$

$$x \left(\tan\omega - \left(\frac{h - F \sin\gamma}{F \cos\gamma} \right) \right) = - \frac{h}{\cos\gamma}$$

$$x = \frac{h\,F}{h - F \sin\gamma - F \cos\gamma \tan\omega}$$

$$x_o = \frac{h\,F}{h - F \sin\gamma}$$

$$\% \Delta m = \frac{\dfrac{h\,F}{h-F \sin\gamma} - \dfrac{h\,F}{h-F \sin\gamma - F \cos\gamma \tan\omega}}{\dfrac{h\,F}{h - F \sin\gamma}} \times 100$$

$$\% \Delta m = \frac{F \cos\gamma \tan\omega}{F \cos\gamma \tan\omega + F\sin\gamma - h} \times 100 \qquad (23)$$

Eq. (23) may also be normalized by defining $Q = \frac{h}{F}$. Then,

$$\% \Delta m = \frac{+\cos\gamma \tan\omega \times 100}{\cos\gamma \tan\omega + \sin\gamma - Q} \qquad (24)$$

Note that $\% \Delta m = 0$ if $\gamma = \frac{\pi}{2}$ which represents conventional optics.

$\% \Delta m$ is small if Q is large ($h \gg F$) and ω small, as might be expected. Figures 5 and 6 are plots of $\% \Delta m$ vs ω for particular values of Q = 1, 2, 3, and 4 and $\gamma = 0°$ and $45°$.

Depth of Field

The primary advantage of the inclined image plane system is an effectively infinite depth of field. However, this infinite depth of field is insured by the foregoing equations only in the plane of the object surface. If a three-dimensional terrain model is used, there is a limit on the height of terrain which will be within this depth of field. The following discussion

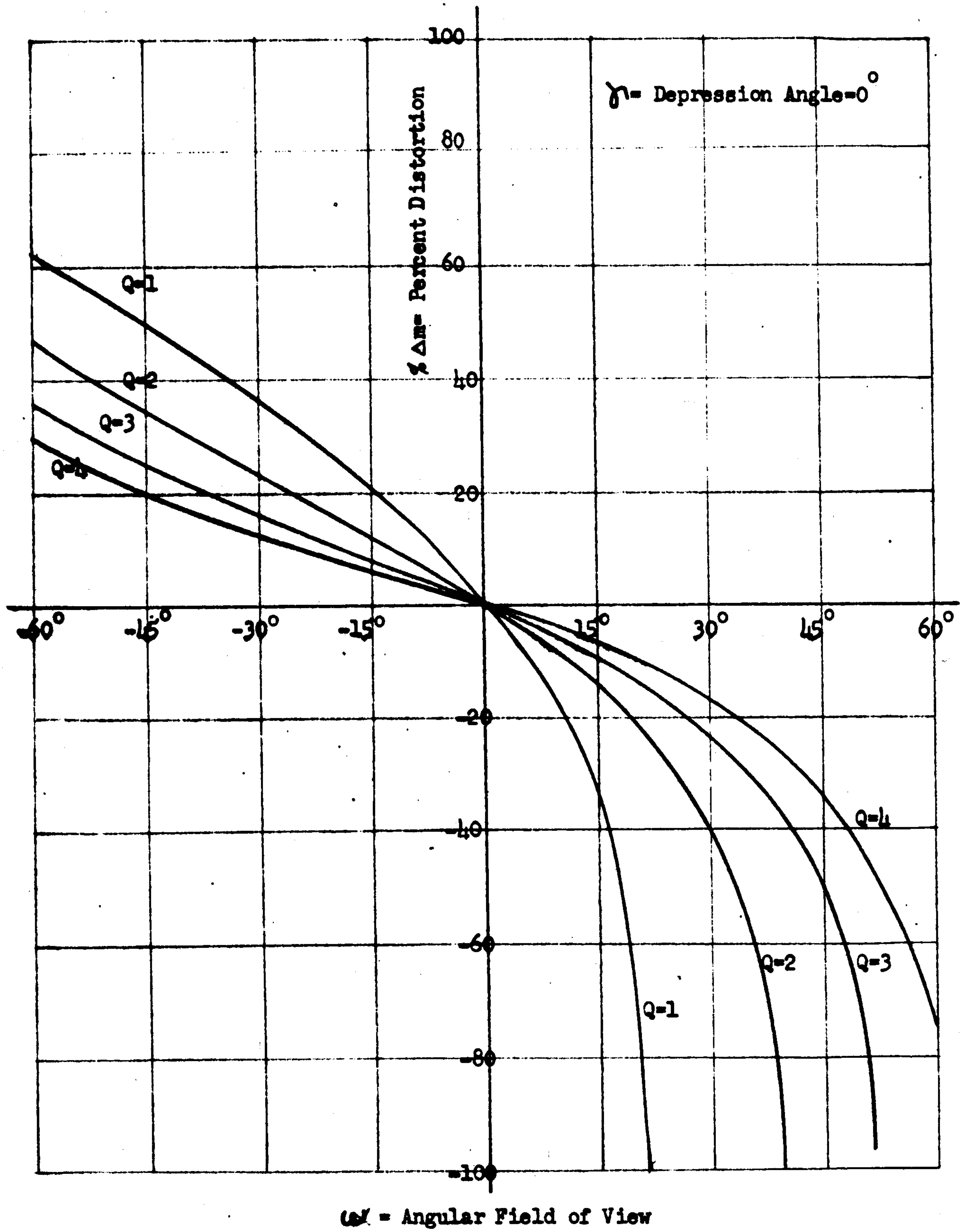


Figure 5 : %Δm vs. ω

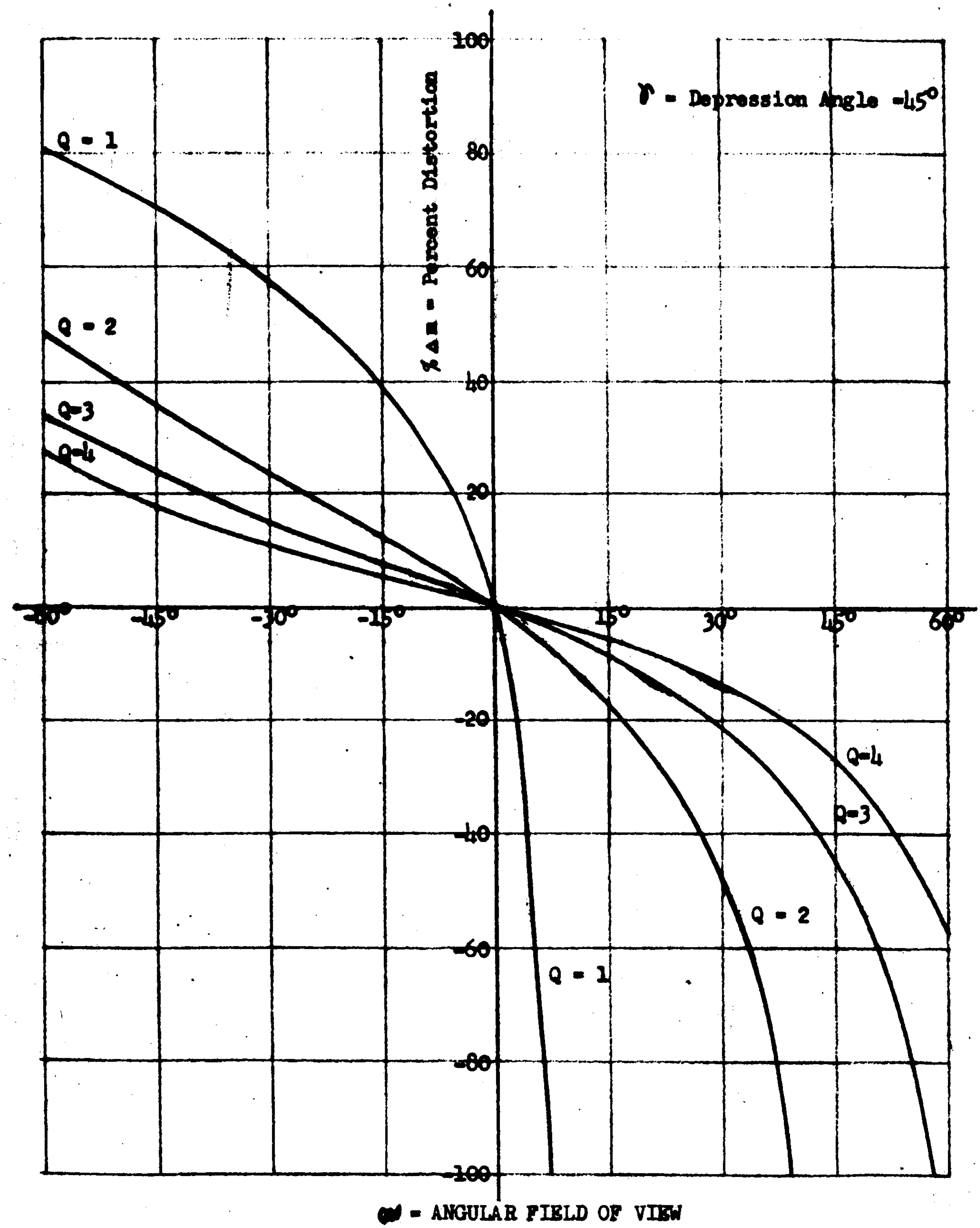


FIGURE 6: %Δm VS ω

analyzes the depth of field and the improvements which can be made to optimize focusing in the height dimension.

Nominal Depth of Field

The Equations for the near depth of field (D_N) and the far depth of field (D_F) are:

$$D_N = \frac{H\, s}{H + (s-F)} \tag{25}$$

$$D_F = \frac{H\, s}{H - (s-F)} \tag{26}$$

where H = hyperfocal distance = $\frac{F^2}{(f/no)\ \ C}$

f/no. = relative aperture

C = circle of confusion

In conventional optics the object distance is considered constant over the field of view of the lens, so the near and far depths of field are fixed normal to the optical axis provided the other parameters do not change. But in the case of oblique optics, s is constantly varying across the field, and D_N and D_F vary with it as a function of altitude, depression angle and instantaneous look angle. In order to evaluate the depth of field, general equations of s as a function of appropriate parameters are needed.

From Figure 1 , the slant range R_s is given by:

$$R_s = h \csc \delta \tag{27}$$

The ground range R_g is similarly found:

$$R_g = h \cot \delta \tag{28}$$

The object distance s is:

$$s = R_s \cos(\delta - \gamma)$$

$$s = \frac{h\cos(\delta - \gamma)}{\sin\delta} \qquad (29)$$

Thus the near and far depths of field can be found for any set of parameters. Figures 7 through 13 are graphs relating any set of parameters to depth of field. As an example, suppose the pilot has a ground range on the model of 1.40 inches at an altitude of 1.0 inches. From figure 8, his instantaneous look angle is $-40°$. If his vehicle's depression angle is $-60°$, the object distance (from figure 11) is $s = 1.41"$. A set of curves such as those shown in figure 13 will give the near and far depths of field. In this case ($F = 0.10"$, $C = 0.00184"$), if the pickup is operating at f/5, $D_N = 0.62"$ and $D_F = \infty$. This data implies that any information such as a mountain, located as high as 0.62 inches off the model surface will be in acceptable focus on the oblique image plane.

The usable depth of field can be found from:

$$D = s - D_N$$

$$D = \frac{s^2 - sF}{H + s - F}$$

Substituting $H = \frac{F^2}{(f/no)C}$, we have

$$D = \frac{s^2fC - sFfC}{F^2 + sfC - FfC} \qquad (30)$$

Figure 14 shows a plot of the usable depth of field, D, as a function of the object distance, s.

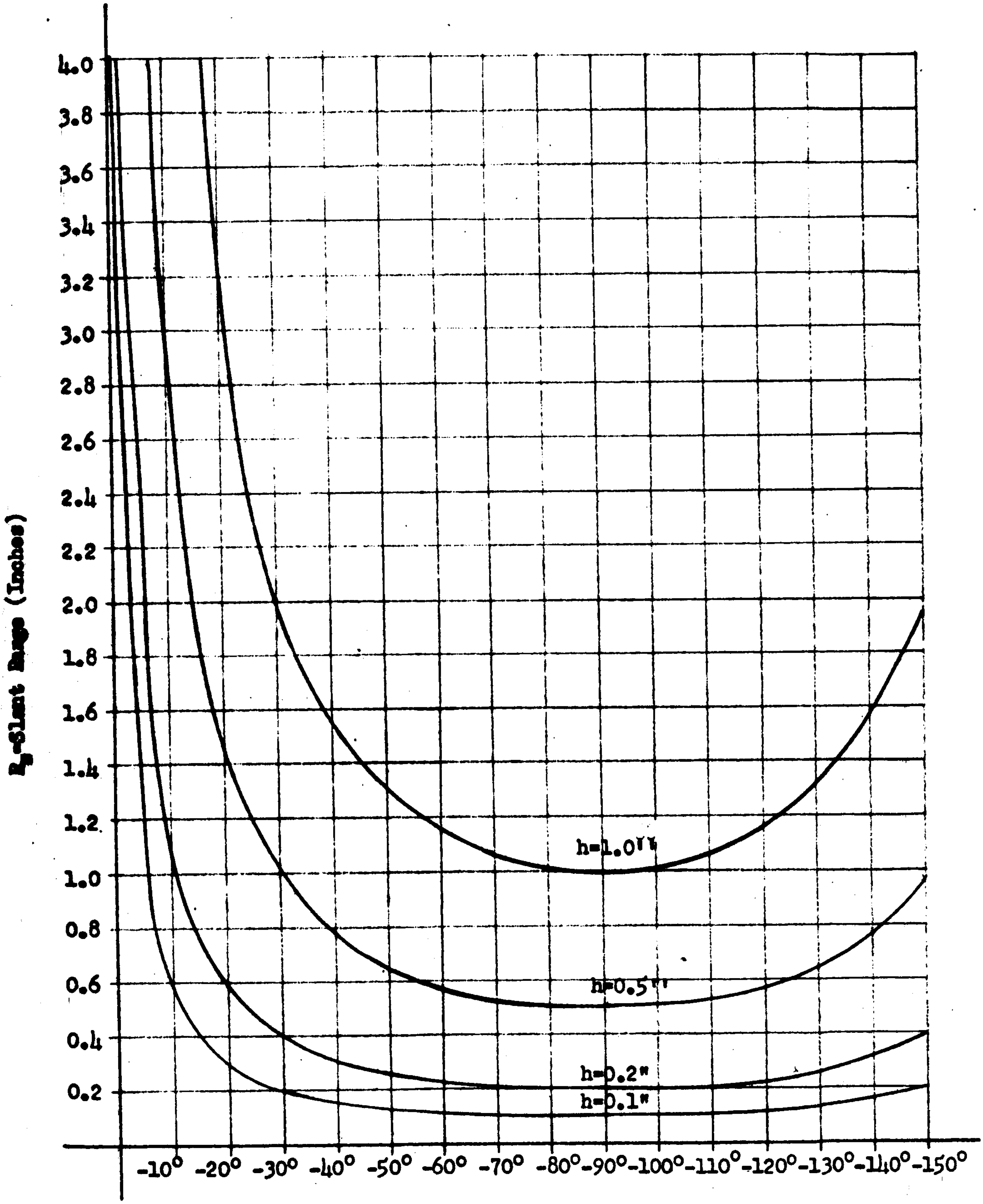


Figure 7: R_s vs. δ

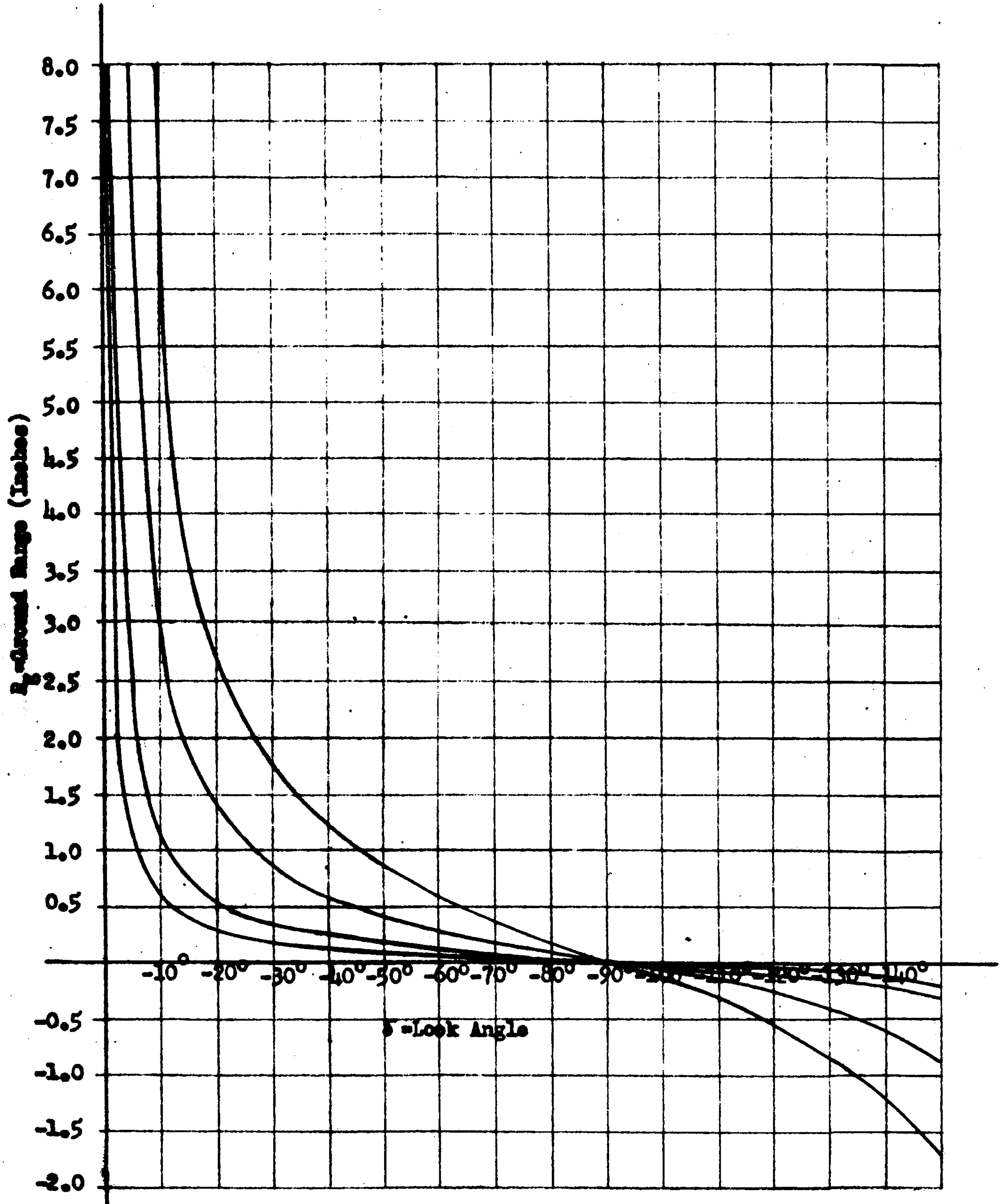


Figure 8 : R_g vs. δ

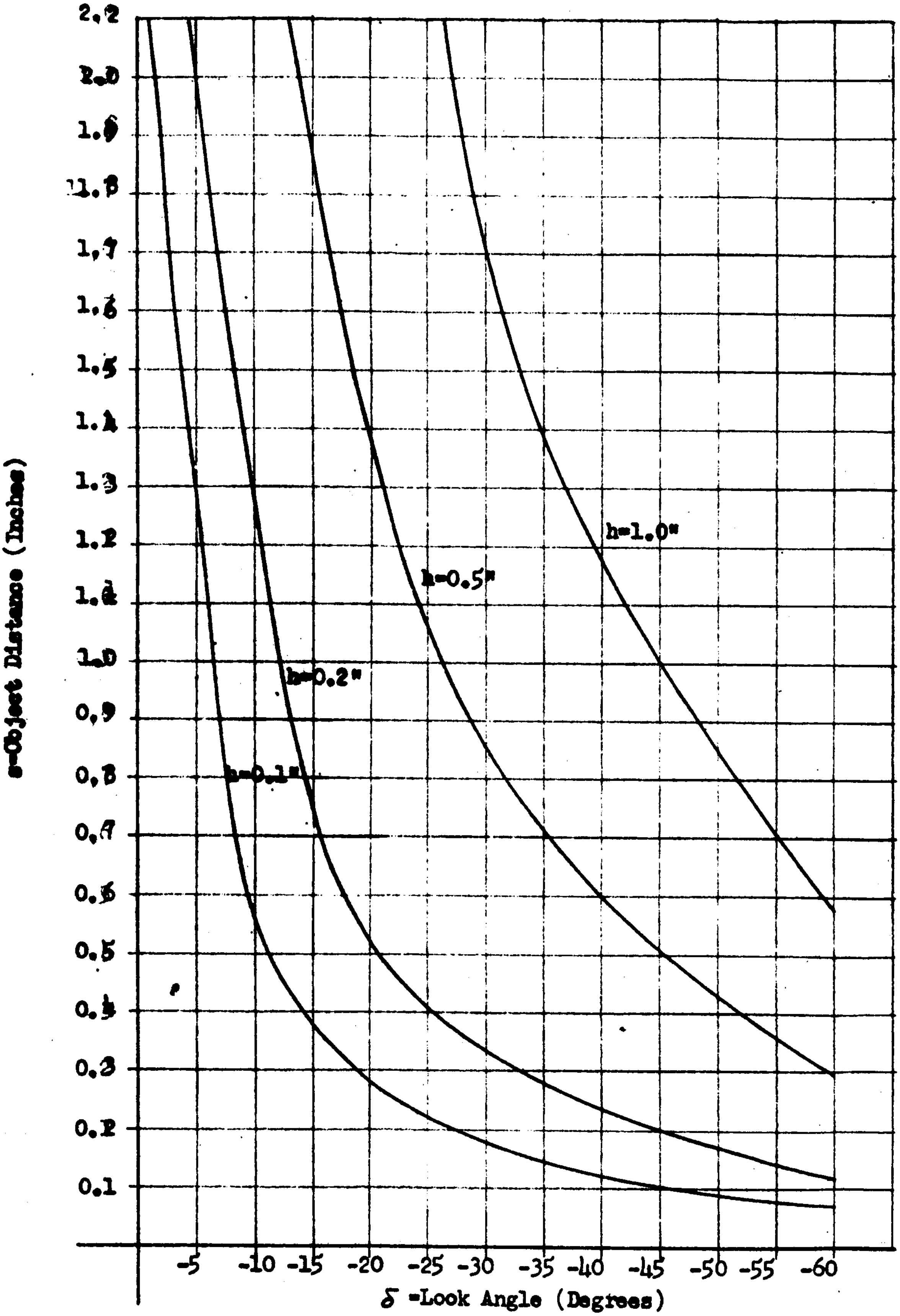


Figure 9 : s vs. δ; γ =0°

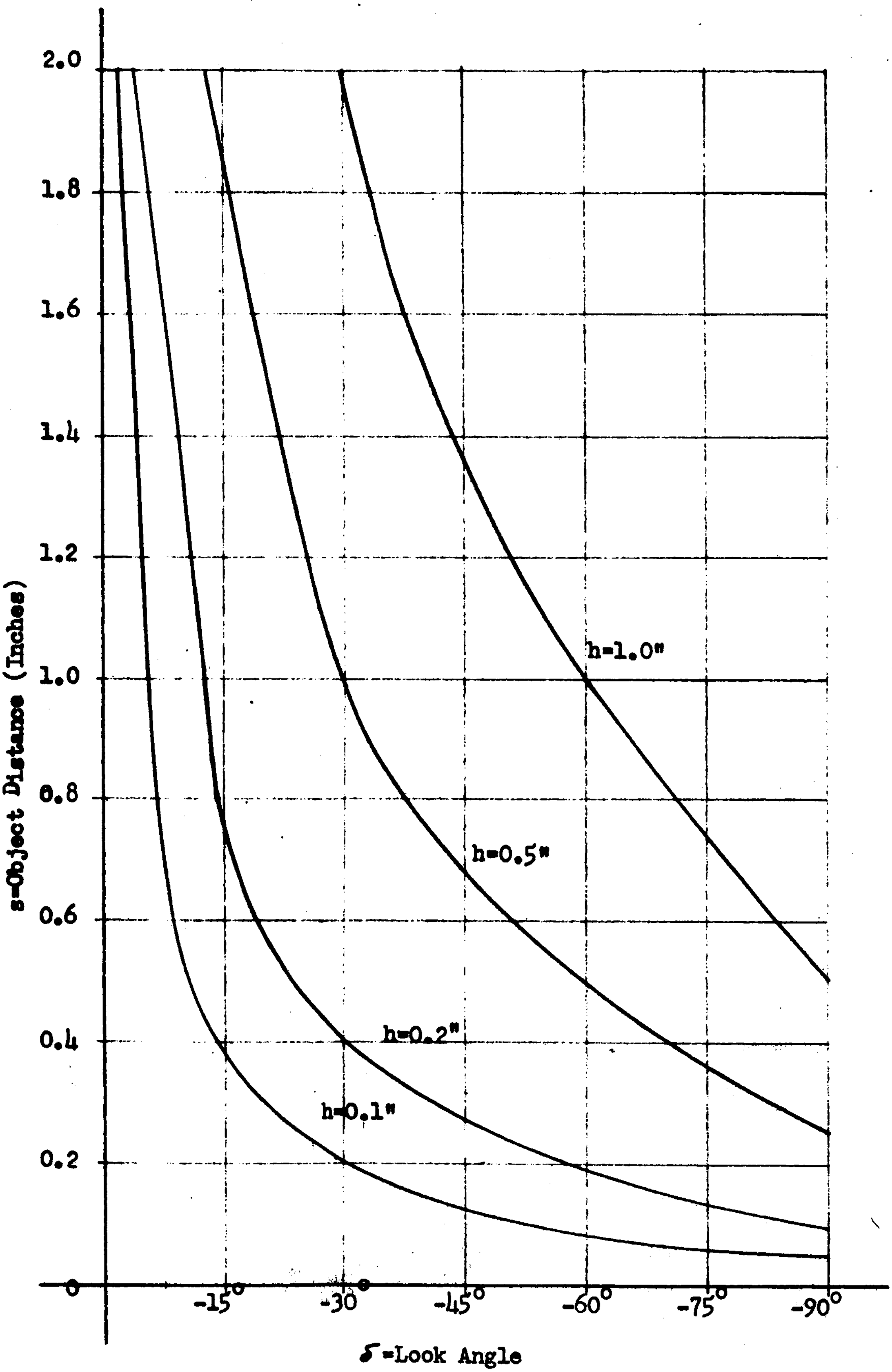


Figure 10: s vs. δ ; γ=30°

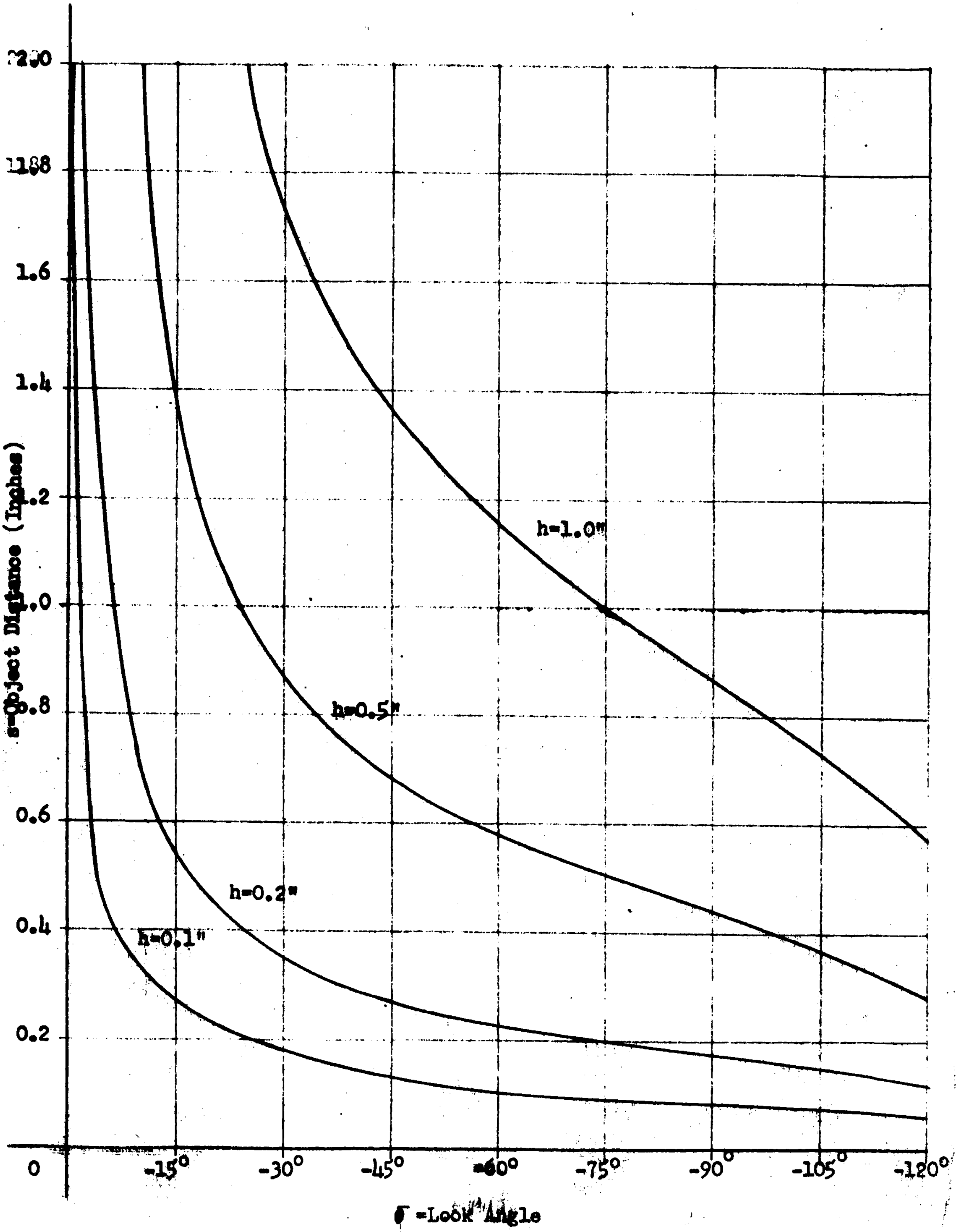


Figure 11 ; s vs. δ ; γ=60°

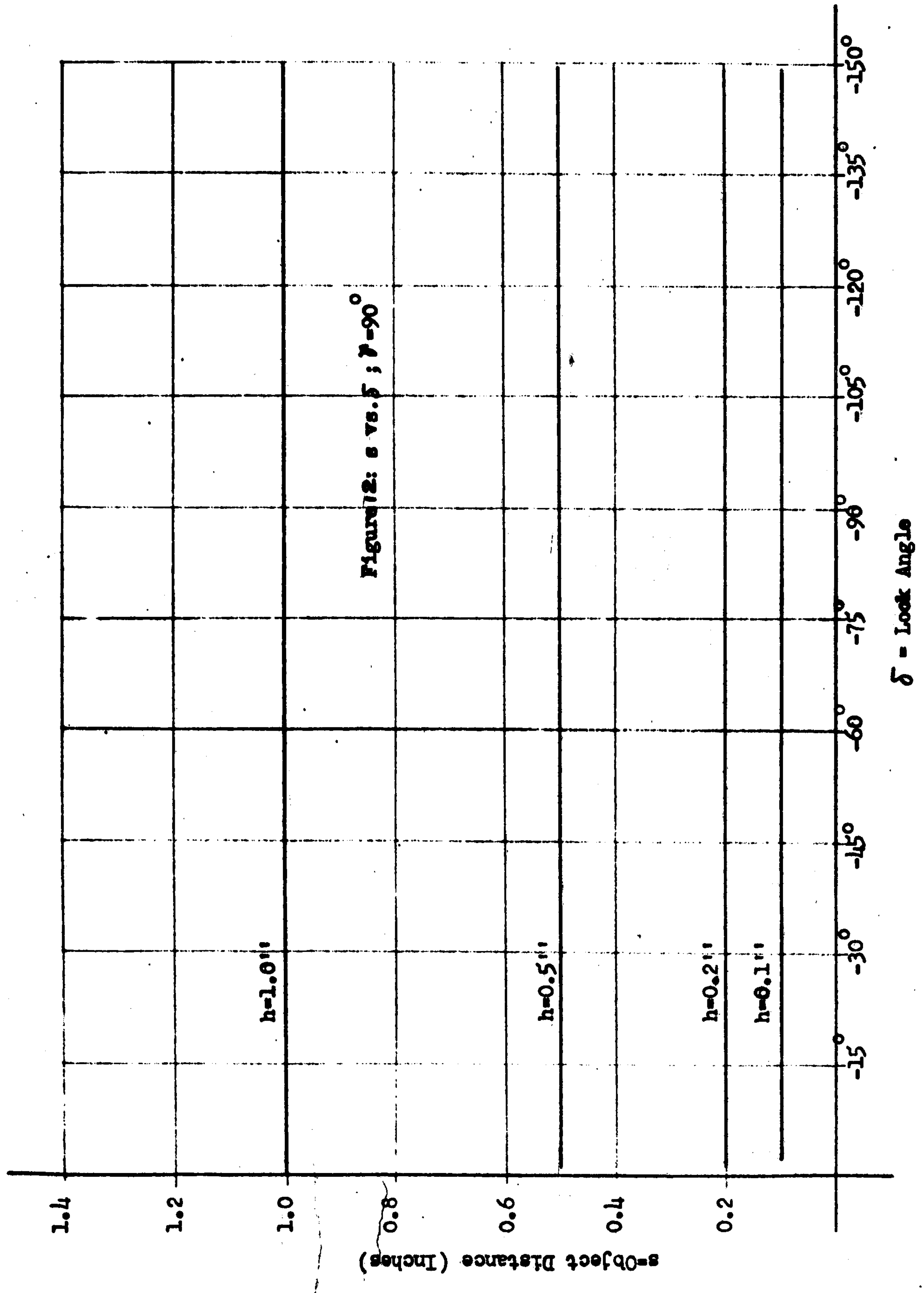


Figure 12: s vs. δ ; γ=90°

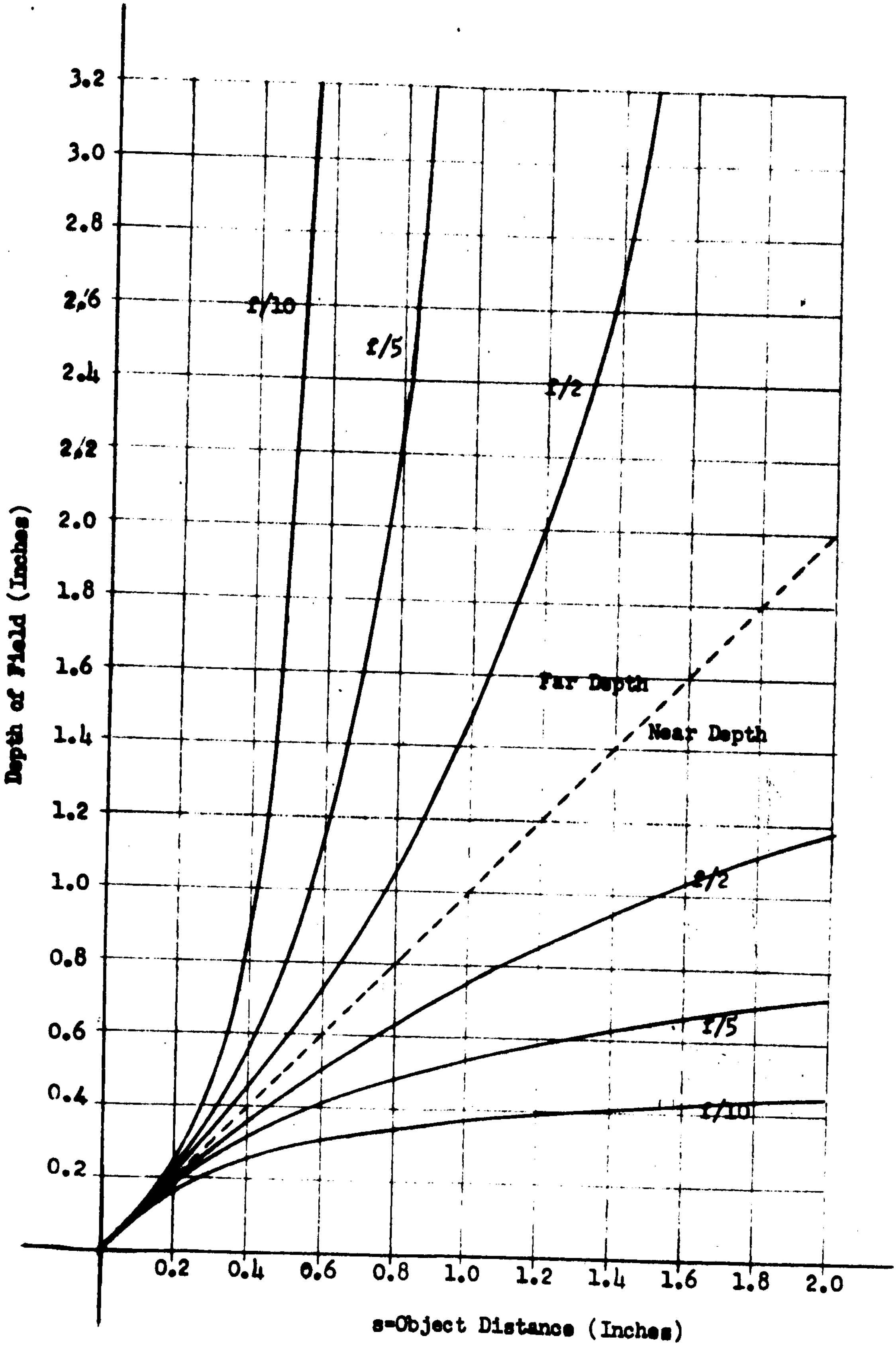


Figure 13: D_N, D_F vs. s

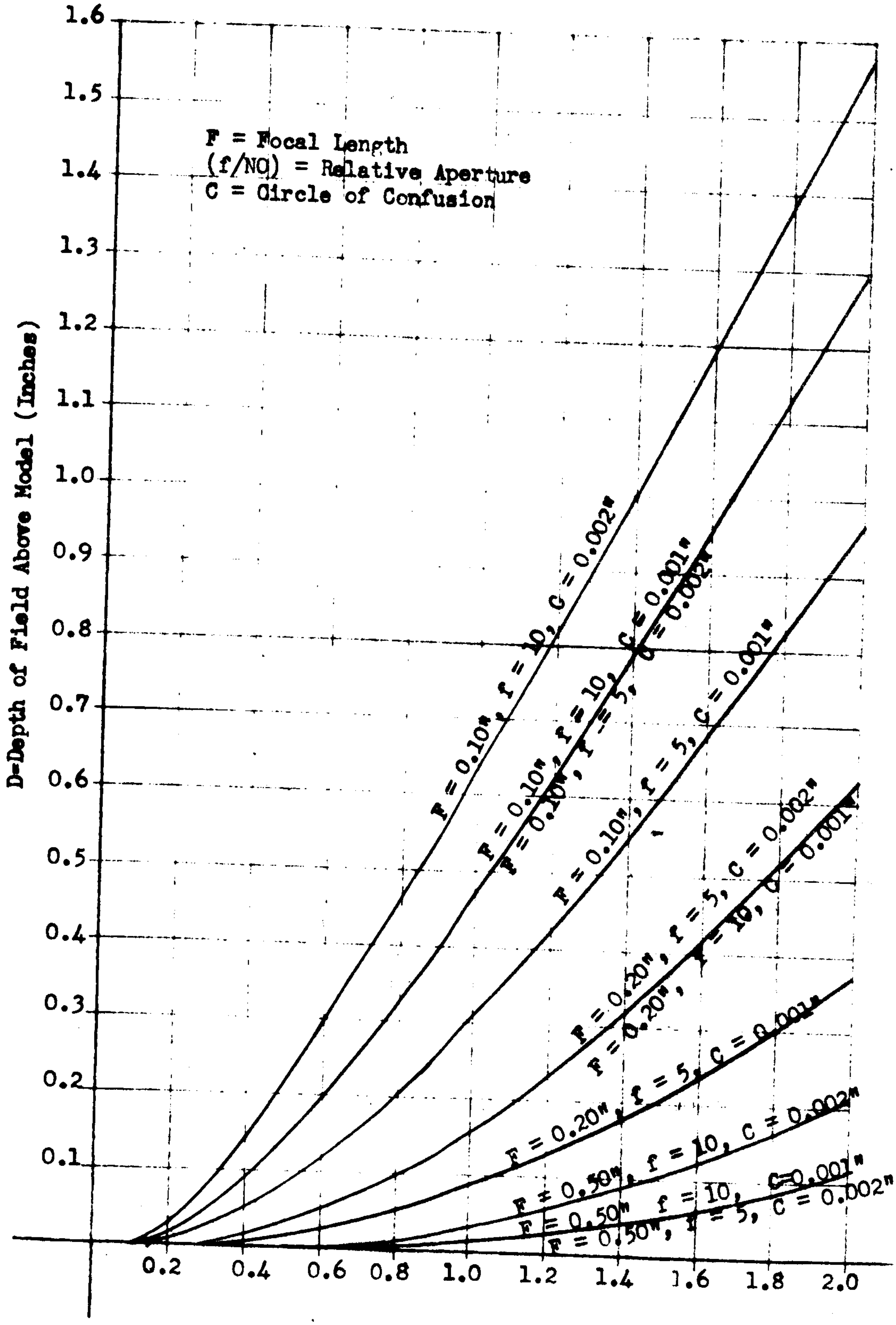


FIGURE 14 - D vs s s = OBJECT DISTANCE (Inches)

Optimized Depth of Field

From Section IV, 3, a , the far depth of field is not utilized because it is below the model surface. The usable depth of field can be increased by focusing not on the object plane, but on an imaginary plane above the model surface (see figure 15). The usable depth of field is then optimized when the far depth of field lies at the object plane or at some convenient vertical datum in the case of a terrain model.

Define an imaginary object surface S' such that $D_F' = s$.

Then, from eq. (26)

$$\frac{HS'}{H - S' + F} = s$$

$$S' = \frac{s(H + F)}{(H + s)} \qquad (31)$$

The near depth of field is then

$$D_N' = \frac{HS'}{H + S' - F}$$

Substituting eq. (31)

$$DN' = \frac{Hs\ (H + F)}{H(H+s)\ +s(H+F)-F(H+s)}$$

$$D_N' = \frac{s(H+F)}{H + 2s - F} \qquad (32)$$

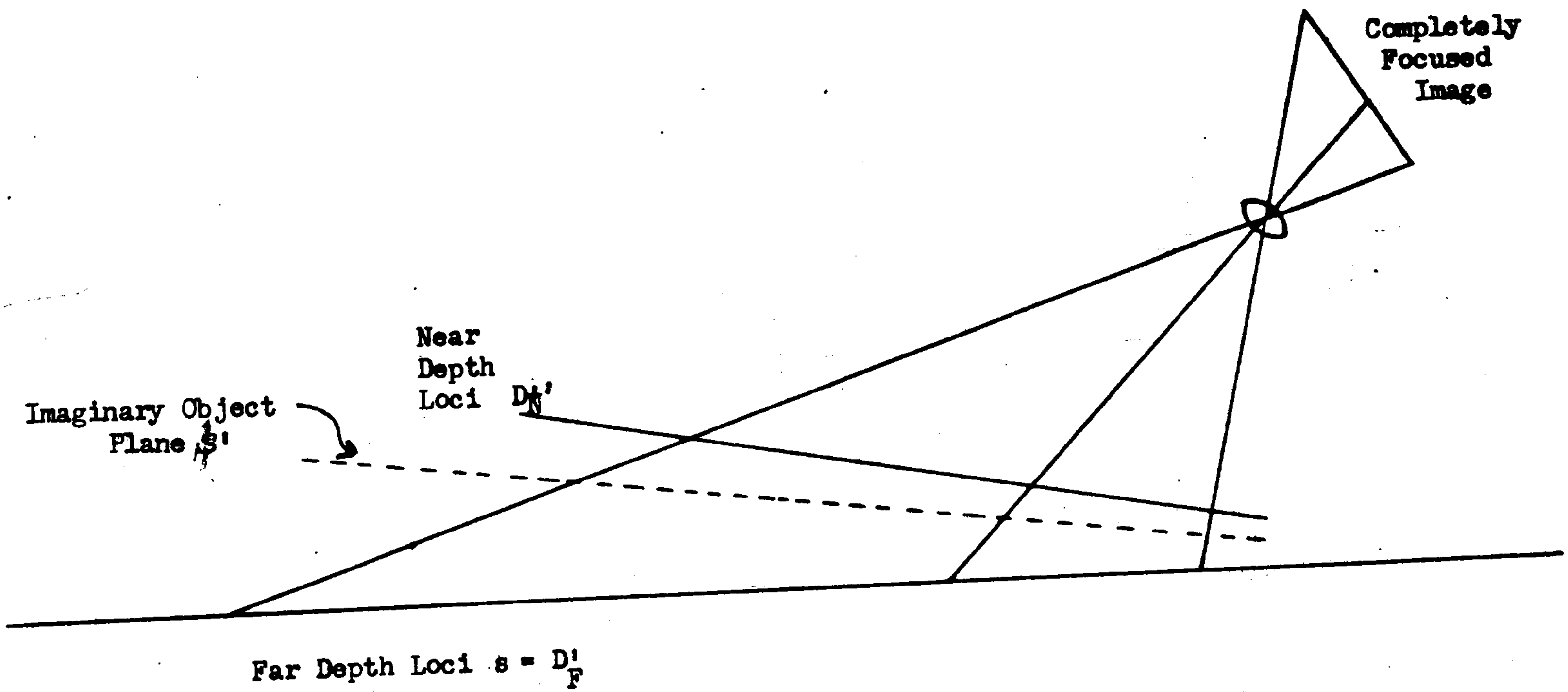


FIGURE 15 - OPTIMIZED DEPTH OF FIELD

The usable depth of field is $D_F' - D_N' = D'$

$$D' = s - \frac{s(H + F)}{H + 2s - F}$$

$$D' = \frac{2s(s - F)}{H + 2s - F} \tag{33}$$

Substituting for H, we have

$$D' = \frac{2sfC\ (s - F)}{F^2 + 2sfC - FfC} \tag{34}$$

Figure 16 shows a plot of the optimized usable depth of field, D', as a function of the object distance, s. A comparison of figures 14 and 16 readily shows that $D' > D$ for equivalent values of s.

The percent of increase in depth of field, $\% \Delta D$, can be found from the general equation of percentage difference..

$$\% \Delta D = \frac{D' - D}{D} \times 100 \tag{35}$$

Putting eqs. (30) and (34) for D and D' into (35), we have, after factoring,

$$\% \Delta D = \frac{F^2 - FfC}{F^2 - FfC + 2sfC} \times 100 \tag{36}$$

Figure 17 shows a plot of $\% \Delta D$ vs. s for several values of F, f, and C. The percentage increase is larger for greater values of F.

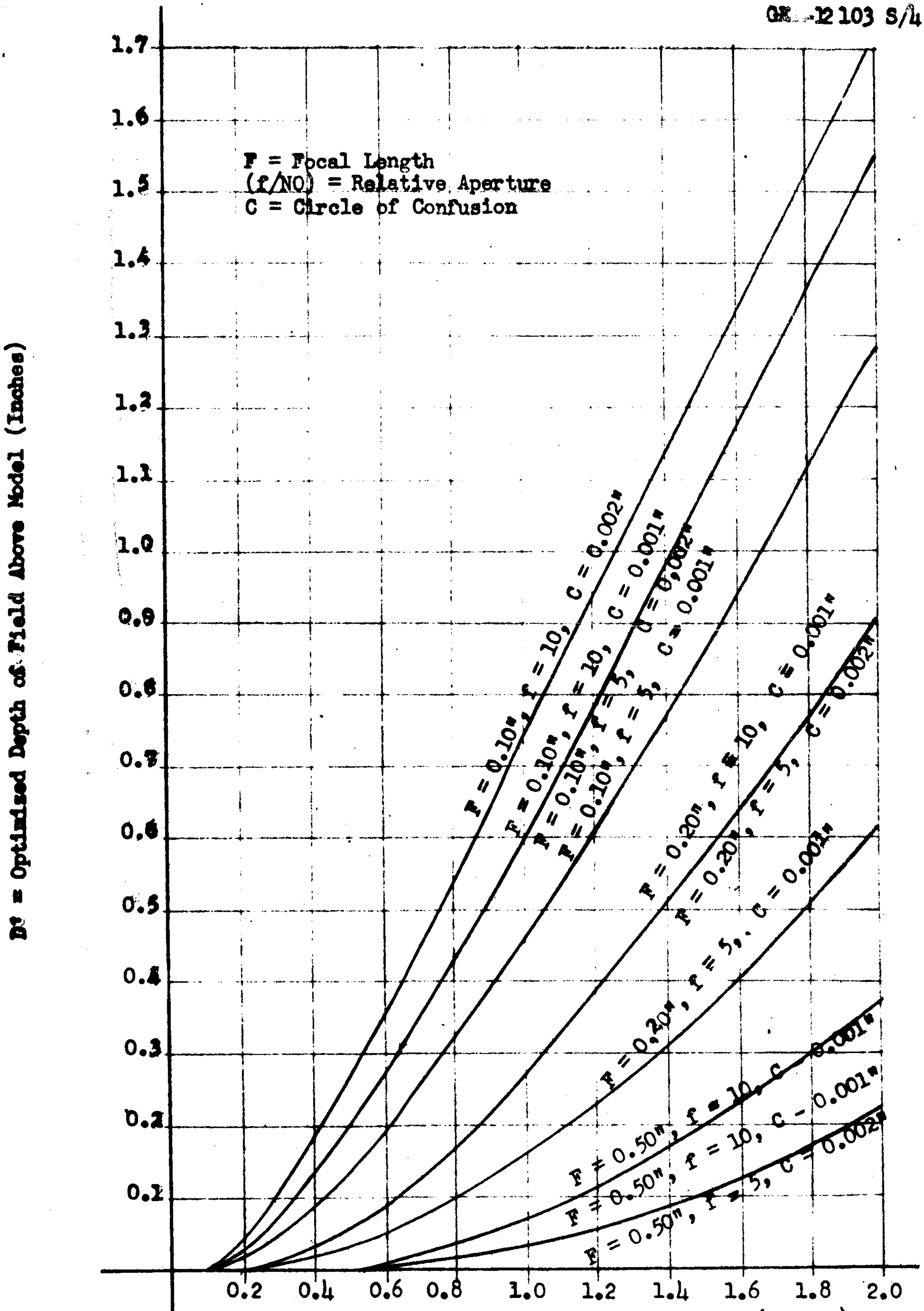


FIGURE 16 – D' vs s   s = Object Distance (Inches)

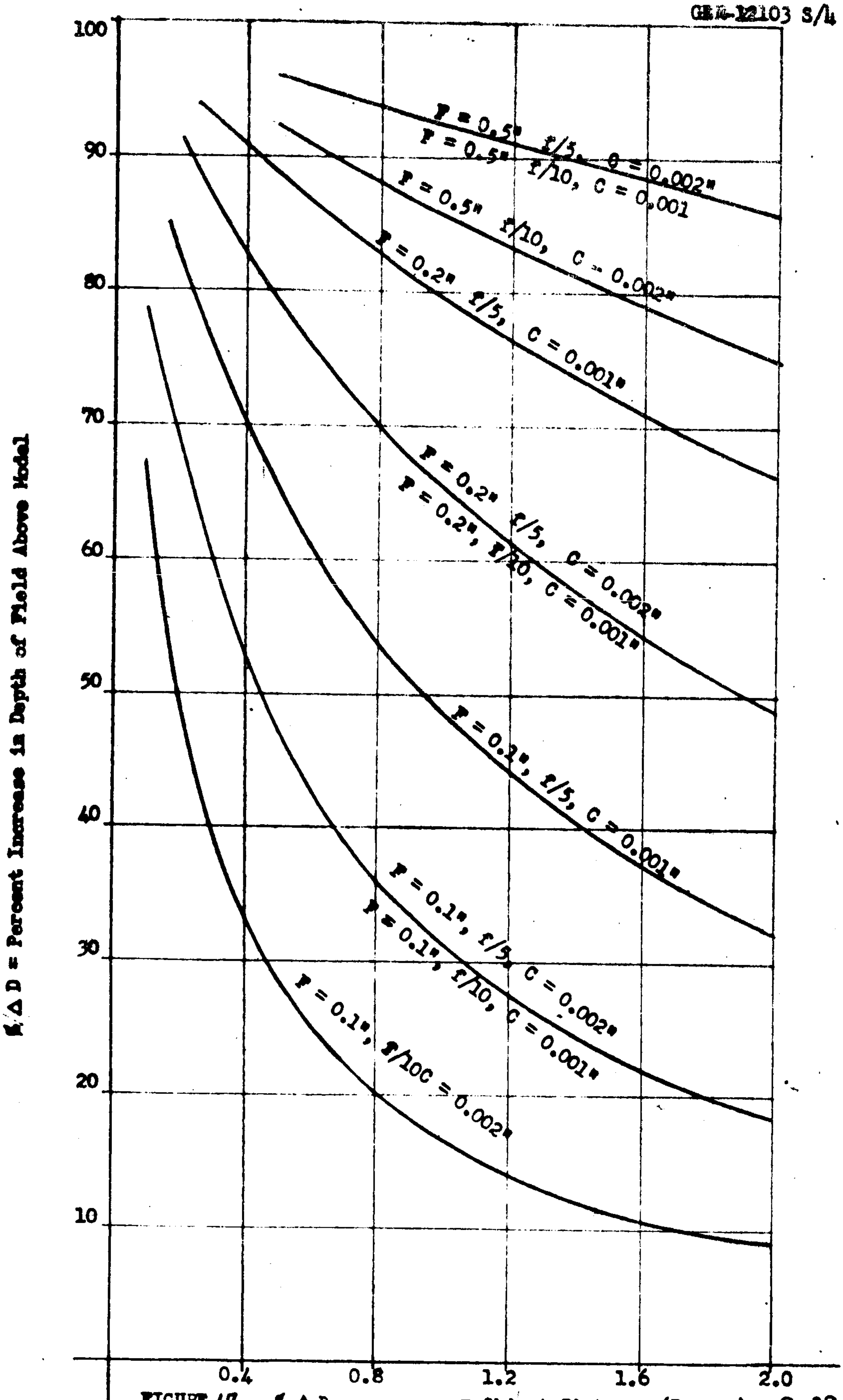


FIGURE 17 – % Δ D vs s

APPENDIX H - TELEVISION SYSTEM DATA

The following is a description of the current state of the art in television systems - particularly the pickup tube area. Primary interest is directed toward high-resolution systems.

Table I lists some of the important characteristics of three high-resolution camera systems presently available. Table II tabulates many of the important mechanical and electrical parameters of a number of different pickup tubes.

Television display monitors (black and white) to be used in conjunction with the camera systems of Table I are available in 14, 17, and 21-inch models. These monitors can be used at scan rates up to 1215 lines per frame (36.45 kilocycles) and have video bandwidths of about 22 megacycles ± 1 db. Other monitors are available with video bandwidths of up to 30 megacycles but require modification to obtain the higher scan rates (1203 lines per frame).

Television projectors, utilizing high-intensity cathode ray tubes with Schmidt optical systems are currently available with scan rates up to 819 lines per frame (24.57 kilocycles) and maximum video bandwidths of about 10 megacycles. These projectors are not compatible with the high-resolution camera systems of Table I. It is questionable if suitable Schmidt projectors for this use will ever be built since the resolution capability of the optical system itself, as well as the projection tube performance, becomes a limiting factor in the final display quality. Control-layer systems such as the Eidophor or the G.E. Light-Valve projectors provide higher resolution and very high brightness displays, although at increased cost and equipment complexity. Light-Valve projectors have been produced utilizing 1029 line scan rates with 20 mc video bandwidths and have demonstrated horizontal resolution in excess of 700 TV lines.

Two types of pickup tubes not listed in Table II but of interest are an all-electrostatic image orthicon developed by G.E. and a vidicon utilizing secondary electron conduction developed by Westinghouse. These tubes have many important advantages (sensitivity, lag characteristics, dynamic range, etc.). However, at the present time resolution capabilities prohibit their use in the high-resolution television systems discussed above.

TABLE I - HIGH RESOLUTION CAMERA SYSTEMS

	1 Inch Vidicon System	1½ Inch Vidicon System	3 Inch Image Orthicon System
Scan Rate in Lines per Frame	1029	1203	1029
Frame Rate in Frames per Second	30	30	30
Interlace	2 : 1	2 : 1	2 : 1
Horizontal Resolution in TV Lines			
Center	1000	1000	800
Corner	600	700	-
Vertical Resolution in TV Lines	700	795	700
Signal-to-Noise Ratio	36 db	-	-
Video Bandwidth in Megacycles	25	32 ± 1 db	20 ± 1 db
Sweep Linearity	± 2%	± 1%	2%
Discernable Gray Scale Shades	10	-	-
Aspect Ratio	1 : 1	4 : 3	4 : 3
Photo Cathode Illumination in Foot-Candles	1	1	.02

TABLE II - PARAMETERS OF SOME COMMERCIALLY AVAILABLE PICKUP TUBES

Tube Type	Vidicon								FPS[g] Vidicon	Plumbicon	Image Orthicon	
Tube Number Designation	8134	8485	8507	C23003	8051	8480	8521	2058G	Z7845	55875	7389B	7967
Parameter												
Max. Tube dia. (in.)	1.13	1.13	1.13	1.14	1.59	1.59	1.59	2.25	1.13	1.19	4.5	3
Overall Tube Length (in.)	6.25	6.25	6.25	6.5	7.75	10.3	7.75	12	≈4.5	8.17	19.4	15.2
Tube Wt. (oz.)	2.8		2		5.3	11	5.3	10	2.1	3.0	37	22
Useful Photocathode dia. (in.)	.62	.62	.62	.62	1	1	1	1.4	.56	.79	1.6	1.8
Focus Method a,b	E	M	M	E	M	E	M	M	M	M	M	M
Deflection Method a,b	M	M	M	E	M	M	M	M	E	M	M	M
Limiting res. in TV lines at center of tube (Uncompensated)	600 700f	1200e	900 1000e	600f	1200 to 1500	1200	1200 to 1500	>2000	800	750	>800	700
Photocathode Illumination (Highlight) Ft.C	2	2	2	.1	6	5	2	15	1-2	.5	.02	2×10^{-5}
Signal to Noise Ratio[c]	← Primarily determined by the video amplifier →										.85	3
Lag[d]	15 to 20%	15 to 20%	20%		25 to 30%	25 to 30%	30 to 45%			<5%		
Spectral Response		S-18			S-18	S-18		S-18	S-18		S-10	S-20
Image Size (in.)	.5x .38	.5x .38	.5x .38	.5x .38	.8x .6	.8x .6	.8x .6	1.0x 1.0	.45x .34	.63x .47	1.28 x.96	1.44 x1.08
Ave. gamma of transfer characteristic	.65	.65	.65		.65	.65	.65	.65		.8 to 1.0		

TABLE II (Cont'd.)

FOOTNOTES

(a) M = magnetic

(b) E = Electrostatic

(c) ratio of peak to peak highlight video signal current to RMS noise current for bandwidth of 4.5 mc.

(d) percent of initial value of signal-output current 1/20 second after illumination is removed.

(e) values for high voltage and high focus field strength operation of tube

(f) values for high voltage operation of tube.

(g) FPS = focus projection and scanning mode.

APPENDIX J - SURVEY RESPONDENTS' DATA

General

The information contained in this appendix was contributed by the following organizations:

Identification	Source
Refractive Systems	Scanoptic Incorporated Photomechanisms Incorporated F.B. MacLaren Incorporated
Vue Marq System	Marquardt Corporation- Pomona Division

This data was submitted to GAC for the sole purpose of supporting this study. The first set of data (Refractive Systems) includes certain information which is considered by the respondent to be proprietary, and is so identified on appropriate pages. GAC assumes no responsibility regarding the further dissemination or use of this information by NASA, or by others to whom NASA may subsequently make this information available.

Refractive Systems

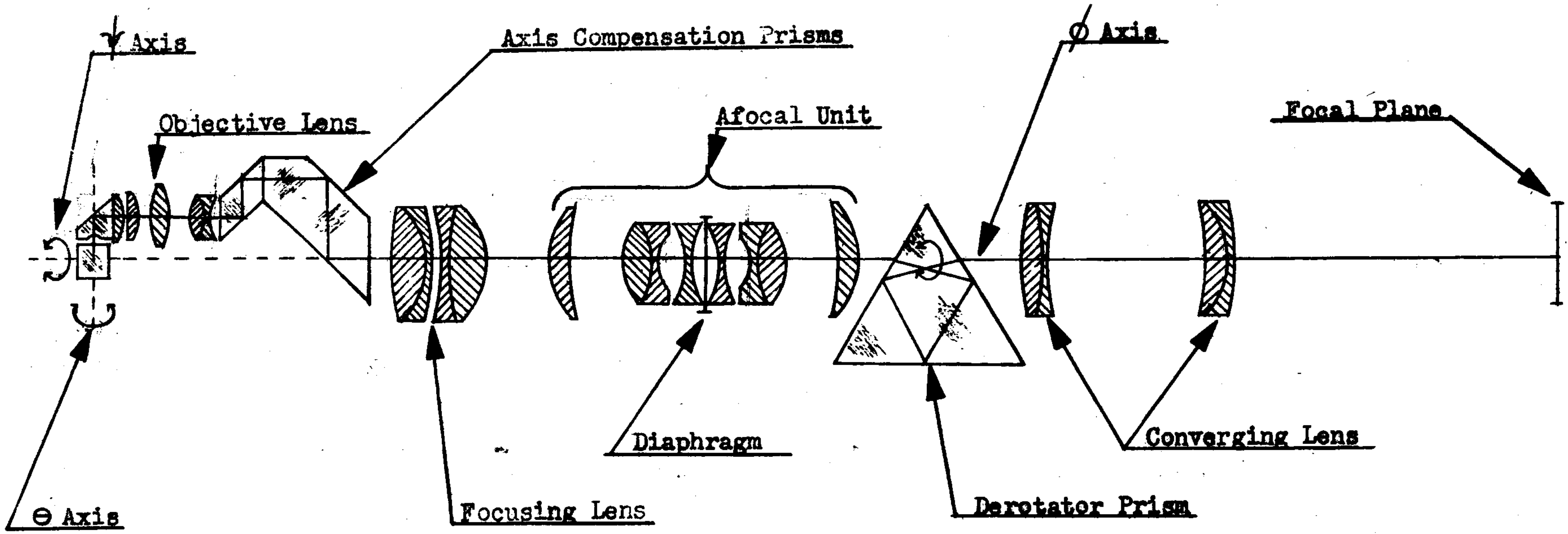
A variety of optical pickup devices have been produced by a team of companies which includes the F. B. MacLaren & Co. Inc., Photomechanisms Inc. and Scanoptic Inc.. Table I is a listing of the optical pickup devices which have been produced by these companies along with the required performance characteristics of each. In some cases these pickups have surpassed specification performance indicated.

These devices all embody the same general design shown in figure 1 , the elements of which are described in detail below.

TABLE I

Characteristics of Servoed Optical Scanners produced by the team of F. B. MacLaren & Co. Inc., Photomechanisms Incorporated, and Scanoptic Incorporated:

Field of View	50°	60°	60°	95°
Image Size	1.6"	.625" 1.6"	1.0"	.625"
F No.	18.9	9.5 24	14.5	8
Resolution (Lines/mm)	56	80 40	55	60
Transmittance (%)	35	40	30	35
Pupil Size (mm)	2	1.6	1.6	1.3
Closest Approach	.25"	.067"	.25"	.25"
Focus Range	.6" to	.5" to	.3" to	.375" to
Azimuth Limits	Cont.	±540°	Cont.	Cont.
Elevation Limits	0-135°	±25°	0-135°	0-170°
Roll Limits	Cont.	±90°	Cont.	Cont.
Azimuth Velocity (Minimum)	45°/sec.	120°/sec.	20°/sec.	60°/sec.
Elevation Velocity (Minimum)	30°/sec.	60°/sec.	20°/sec.	60°/sec.
Roll Velocity (Minimum)	45°/sec.	150°/sec.	20°/sec.	60°/sec.
Azimuth Acceleration (Minimum)	144°/sec.^{2}	120°/sec.^{2}	20°/sec.^{2}	60°/sec.^{2}
Elevation Acceleration (Minimum)	144°/sec.^{2}	150°/sec.^{2}	20°/sec.^{2}	60°/sec.^{2}
Roll Acceleration (Minimum)	144°/sec.^{2}	300°/sec.^{2}	20°/sec.^{2}	60°/sec.^{2}
Accuracy	± 10'	± 30'	± 7.5'	± 10'



COURTESY OF:

SCANOPTIC INC.

PHOTOMECHANISMS INC.

F.B. MacLAREN & CO. INC.

Figure 1 : ANGULAR COORDINATE CAMERA (95° Field of View)

Pitch prisms - Two right-angle articulation prisms are used to simulate pitch. The prism containing the entrance pupil is pivoted about the simulated vehicle's center of rotation. Pivoting of this prism produces both pitch and roll; however, re-rotation of the image is performed further back in the optical chain. The second right angle prism is used to fold the optical path.

Objective lens assembly - this is a short focus group of lenses which form the initial image of the system.

Axis compensation prisms - this prism assembly is used to bring the optical axis of the system into proper alignment with the heading axis of the device.

Focusing lens assembly - The optical function of this group of lenses is to collimate the rays from the image plane of the objective lens assembly. This assembly is servo controlled to focus for the range of object distance required.

Correcting lens assembly - This group of lenses is symmetrical and telescopic. Its function is to compensate for distortions of the instrument. Also, the limiting aperture of the entire system is located at the point of symmetry of this group.

Roll prism - This prism is servo controlled to rotate about the optical axis, thus simulating roll of the final image. The motion of this prism is also coupled with the motion of the pitch prism to compensate for image rotation introduced by the first element.

Converging lenses - The function of this group is to focus the collimated light from the roll prism onto the face of the photocathode.

The entire device is positioned for lateral vehicle motions.

Closeness of approach of these pickups is limited by pitch prism size, prism housing, and the mechanical devices required to pivot the prism. For this reason a slightly different design has been conceived to improve the pickup working distance. This design is shown in Figure 2 . In this design the right angle prism and objective lens assembly are pitched about a remoted pitch axis. This eliminates some of the mechanical structure from the entrance pupil, thereby permitting lower approach. However, this approach would require a coordinate transformation to properly simulate pitch motion. The remainder of the system is identical to that described above.

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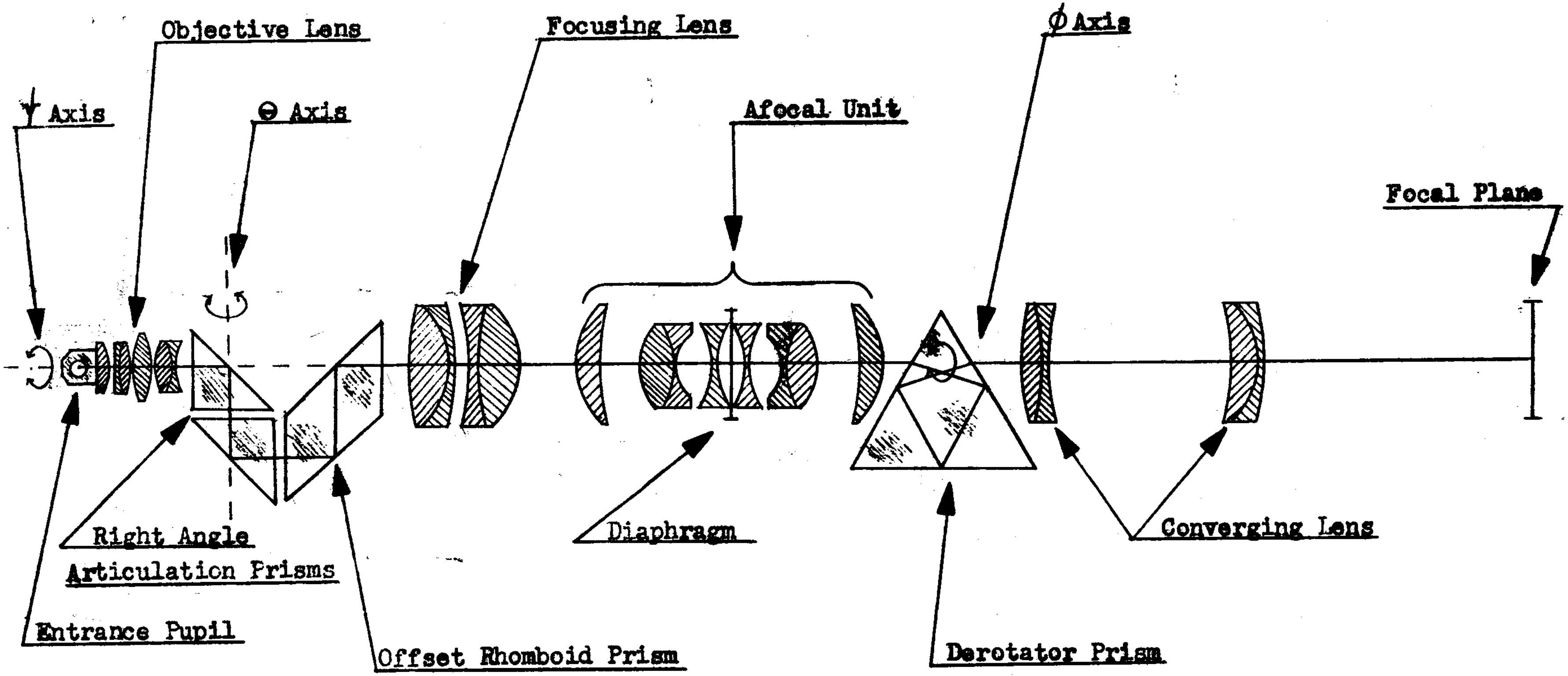
REF: ENGINEERING PROCEDURE S.017



COURTESY OF:

SCANOPTIC INC.

PHOTOMECHANISMS INC.

F. B. MacLAREN & CO. INC.

Figure 2 ; OPTICAL PROBE-REMOTED PITCH AXIS

The VueMarq System

The Marquardt Corporation, Pomona Division, has recently disclosed a real time pickup and display system concept called the VueMarq. The system utilizes the basic principle of reciprocol eccentricity previously discussed in Section III 3.c. Fig. 3 shows a schematic of the system. The system employs special field-correction optics to increase the undisterted field of view. A television system is used as a real time link between the pickup and display systems.

The VueMarq pickup is shown in Fig. 4. It employs a small hyperboloidal mirror, convex toward the model. Since the mirror's external focus is below its convex surface a folding mirror is required to position the additional optical components away from the model surface. Special field shaping optics are used to flatten the otherwise curved field prior to the pickup tube. A microscope objective is used to enlarge the image and focus it onto a one-inch vidicon. The entire device is transported above the model surface for attitude and positional changes.

The VueMarq display is a virtual image system. (Fig. 5). It consists of a kinescope and a special optical projection system for curving the field to conform with the focal surface of the ellipsoidal mirror. A controlled diffusion screen is located at this focal surface and serves to enlarge the display system exit pupil by spreading the light bundle over 10°. This results in a pupil enlargement from about one inch to eight inches.

The Marquardt Corporation's VueMarq system offers advantages not available in previous simulation devices employing the same principle. It is the first device conceived for unprogrammed simulation which combines the basic principle of reciprocal eccentricity with a closed circuit television system as

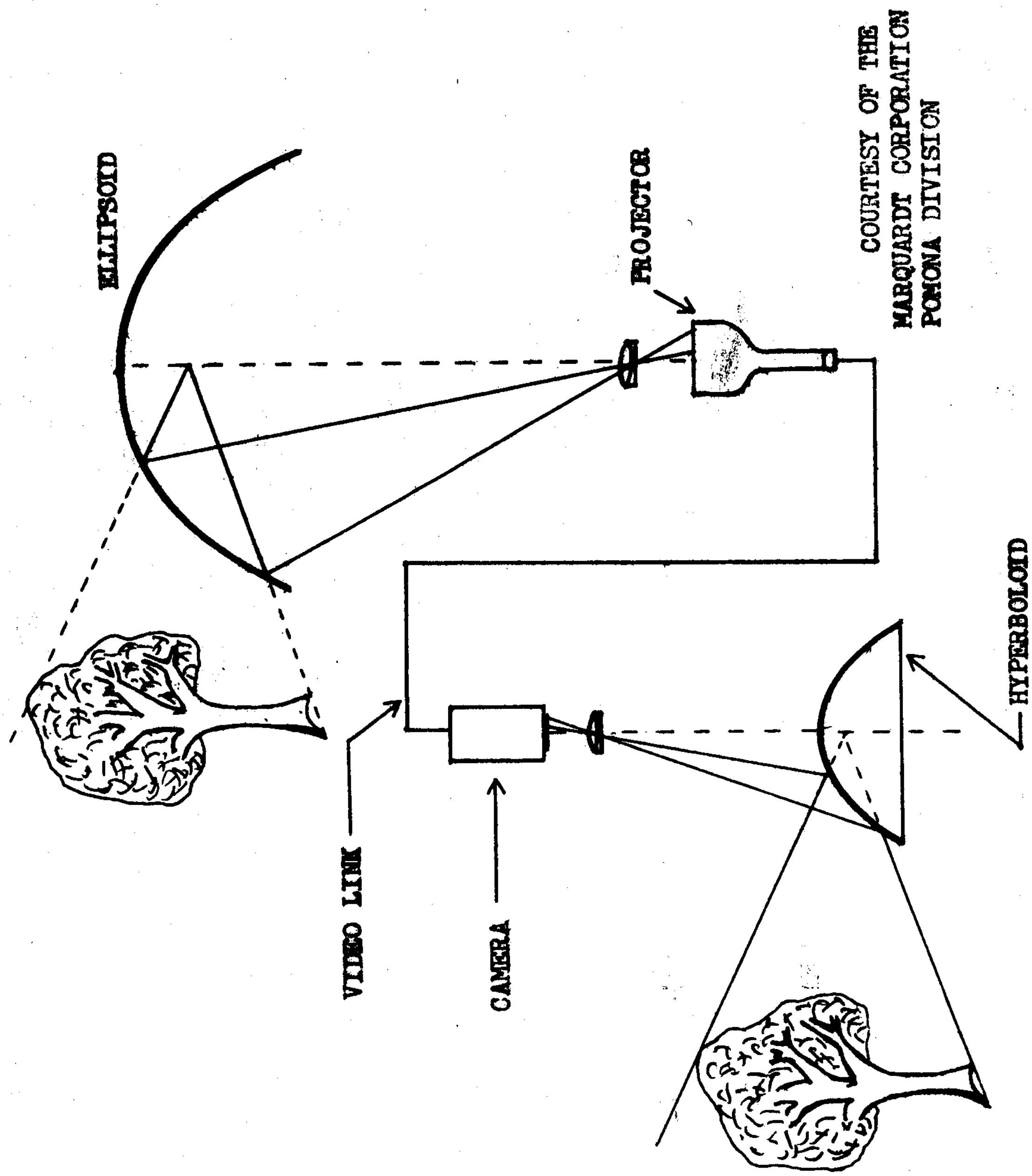


FIGURE 3 - THE "VUEMARQ" SYSTEM

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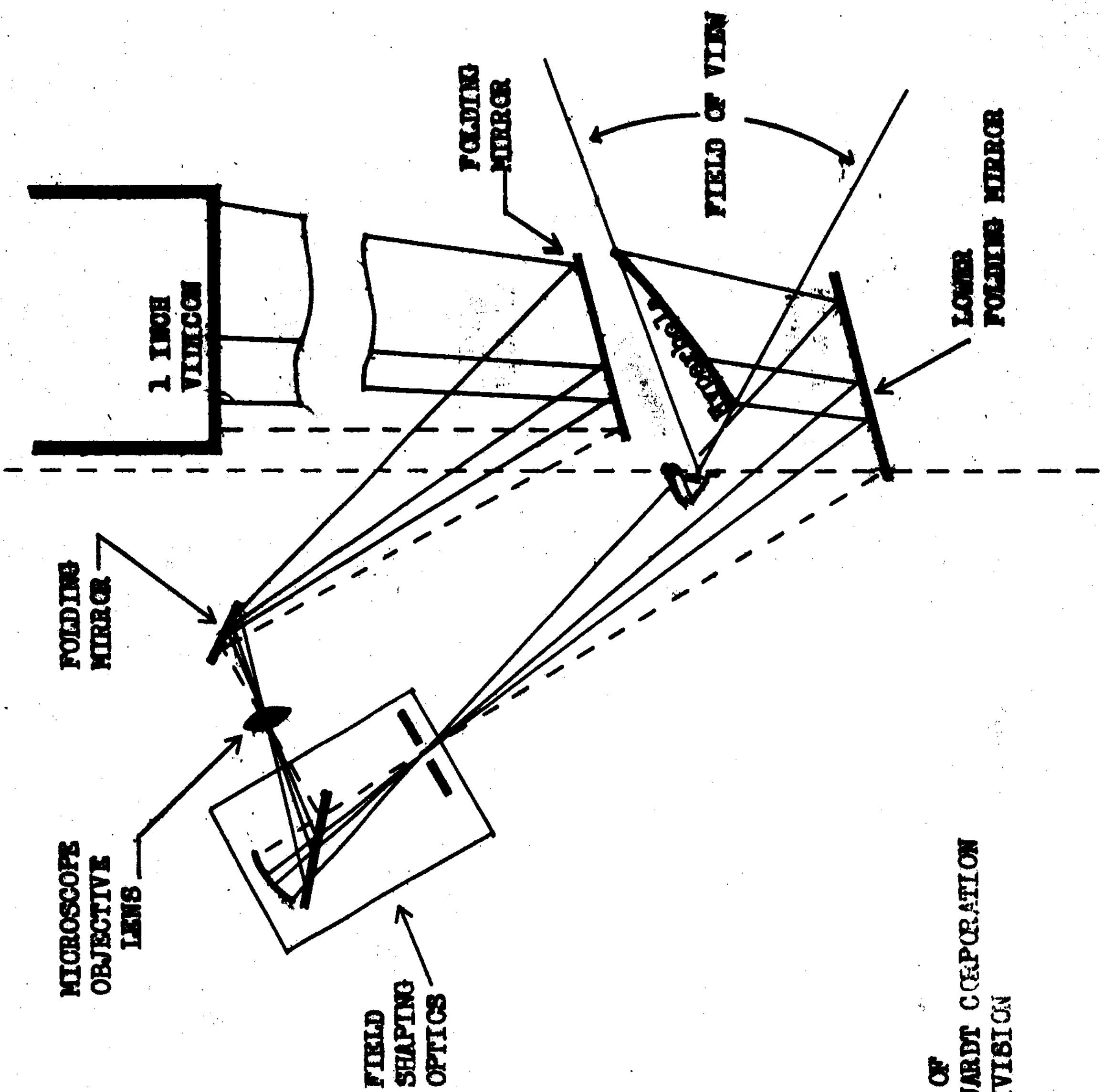

COURTESY OF
THE MARQUARDT CORPORATION
POMONA DIVISION

FIGURE 4 - "VUEMARQ" PICKUP

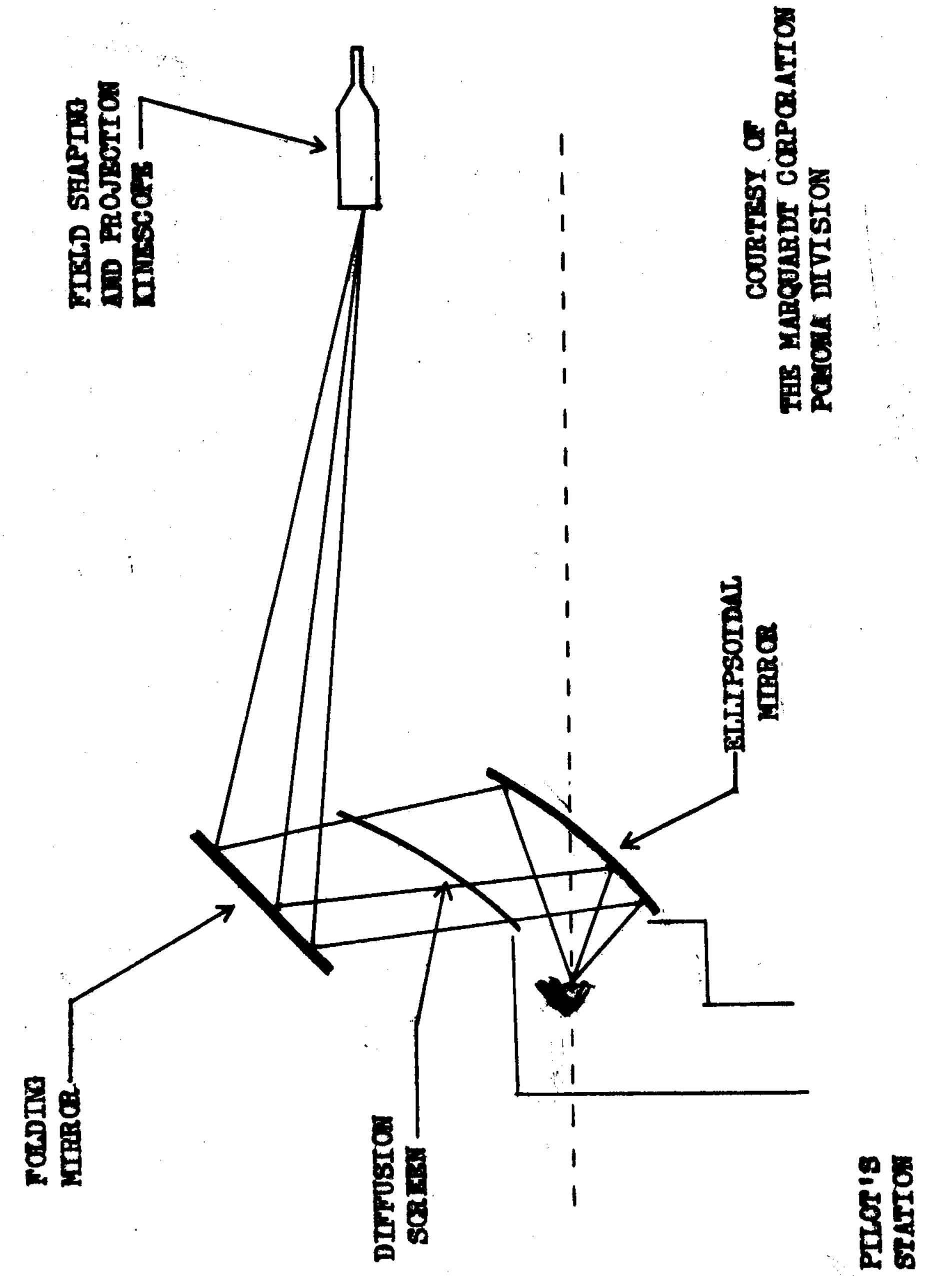

FIGURE 5 - THE VUEMARQ DISPLAY SYSTEM

the link between pickup and display. The field curvature correction system permits the use of a real time transmissive link between pickup and display.

Since the system requires that the optical elements in the pickup be colinear with the line joining the foci of the hyperboloidal mirror, vehicle attitude is simulated by maneuvering the pickup above the model surface. For example, pitch is not simulated by the rotation of prisms or mirrors as in many refractive systems, but by the rotation of the entire pickup device about the entrance pupil point. This can impose severe mechanical design requirements on the system.

Since the entrance pupil is necessarily inside the hyperboloidal mirror, the pickup cannot approach the model as closely as can a system which has the entrance pupil external to the first optical element. The closeness of approach is even more limited in the VueMarq pickup because of the folding mirror located between the hyperboloidal mirror and the model surface.

Another limitation of the VueMarq system is in the display. The inherently small exit pupil is enlarged by the controlled diffusion screen. However, the use of such a screen results in a loss in resolution and display brightness.

APPENDIX K - OTHER OPTICAL SYSTEMS

The Bellarama System

Another system using the above reciprocal eccentricity is the Bellarama system developed by the Bell Aircraft Company. This system is a programmed device employing film as a data link between the pickup and the display. The terrain scene reflected from the hyperboloidal mirror is imaged on the focal plane of a camera. The film data is projected onto a small ellipsoidal mirror which reflects this data onto an ellipsoidal screen for viewing. The camera and projector lenses have the same focal length in order to maintain correct picture geometry. Lens settings of f/16 to f/22 provide the best compromise between image focus and brightness. Difficulty in focusing the curved fields produced by the system reduce the overall field of view capability in elevation to about 60 degrees.

The Opaque Projector

The Cornell Aeronautical Laboratory conducted feasibility studies for using this principle in a direct-viewing system for an automobile simulator. A single portrait lens placed at the external focus of the hyperboloidal mirror focused the image reflected by the mirror onto an elliptical screen. The model scenery was located in a light proof box and intensely illuminated.

The direct view projection system coupled with the large f/nos (f/16) in the pickup and display create unreasonable requirements for illumination, and problems of cooling the models become formidable.

Optical Scanning Systems

One method that has been proposed for obtaining ultra wide angle (120 to 360 degrees horizontally) pickup and display systems utilizes optical scanning techniques. The optical pickup device consists basically of a rotatable mirror or prism positioned above a scale model with its reflecting surface inclined about 45 degrees from the plane of the model, intermediate optics for presenting the scene data to a TV camera pickup tube and the camera electronics. If the mirror (a prism) is rotated about the optical axis then the scene data for the full 360 degrees horizontally is presented to the pickup tube for each complete rotation of the mirror. A radial scan, rotating in synchronism with the mirror, in the pickup tube can be used to read out the visual data presented to the tube. The video signals generated by the camera can be used to drive a TV projector which employs a radial scan synchronized with the camera. The TV display is projected through appropriate optics to a rotating mirror (rotating synchronously with the camera mirror) and then to a wide-angle cylindrical screen for display to an observer(s). The display thus generated is an exact wide-angle reproduction of the visual imagery "seen" by the "scanning camera". The mirror rotation rate would be 3600 rpm (60 cps) and a 2 to 1 interlace employed in the TV equipment.

The basic system described above is potentially capable of providing a 360 degree horizontal field of view to an observer, however it has several basic problem areas. Mechanical design problems, physical size and instruction, associated with a rotating mirror or prism arrangement would not allow as close an approach to the scale model as can be achieved with other optical pickup devices, hence model size for a given area will increase and attitude motion requirements become more difficult to implement.

Synchronization between mechanical and electrical elements could cause problems. Light output requirements of the projector are very high in order to obtain a usable display on the screen.

State of the art pickup tube lag characteristics and limiting resolution capabilities (both inherent tube limitations and system video bandwidth limitations) will limit the 360 degree display resolution to a relatively low value.

Another approach to optical scanning systems is to use a small spherical mirror placed just above the model surface and oriented so that a full 360 degree (horizontally) scene is continuously presented to the TV pickup camera optics. This same effect can be accomplished by utilizing a 180 degree hemispherical lens. In a Design Study For V F S - 2 MELPAR INC. recommended use of the latter technique for an optical pickup system (this system viewed a transparency). This device will be discussed briefly below:

The first optical element of the pickup device was to be a wide angle 180 degree lens having a short focal length. This objective lens was to obtain a 360 degree view of the terrain data directly below. This lens produces predictable image distortions that are a function of the off-axis angle; however, a flat image surface (plane) can be obtained for transmission of the image through the rest of the optical and electronic systems. The image was to be projected through a similar 180-degree lens at the display and thus recreating true perspective.

A condensing lens was to be placed after the objective lens. A servoed focusing lens was used to keep the image focused on a scanning prism. This prism was to be a simple Schmidt-Pechan derotator which would be rotated at a constant speed of 3600 rpm, the image thus rotating at a rate of 7200 rpm. A single radial line of fiber optic ends (600 fibers) was to be placed in the image plane with each fiber connecting to a separate photo diode. Thus as the prism rotated, the image would be scanned at a rate of 120 times per second. The output of each of the photo diode sensors was to be amplified, requiring 600 amplifiers, and transmitted to 600 miniature cathode ray tubes for projection to the viewer. The effective video bandwidth of this system would be over 300 meagcycles even though individual amplifier bandwidth would be about 650 kilocycles. This device was to have a resolution capability of 4 minutes of arc. All aircraft attitude and positional motions were to have been simulated.

The above device would overcome some of the problems associated with 360-degree optical scanning devices such as resolution and lack of rotating components close to the model surface; however, total system complexity would present many difficult problems.